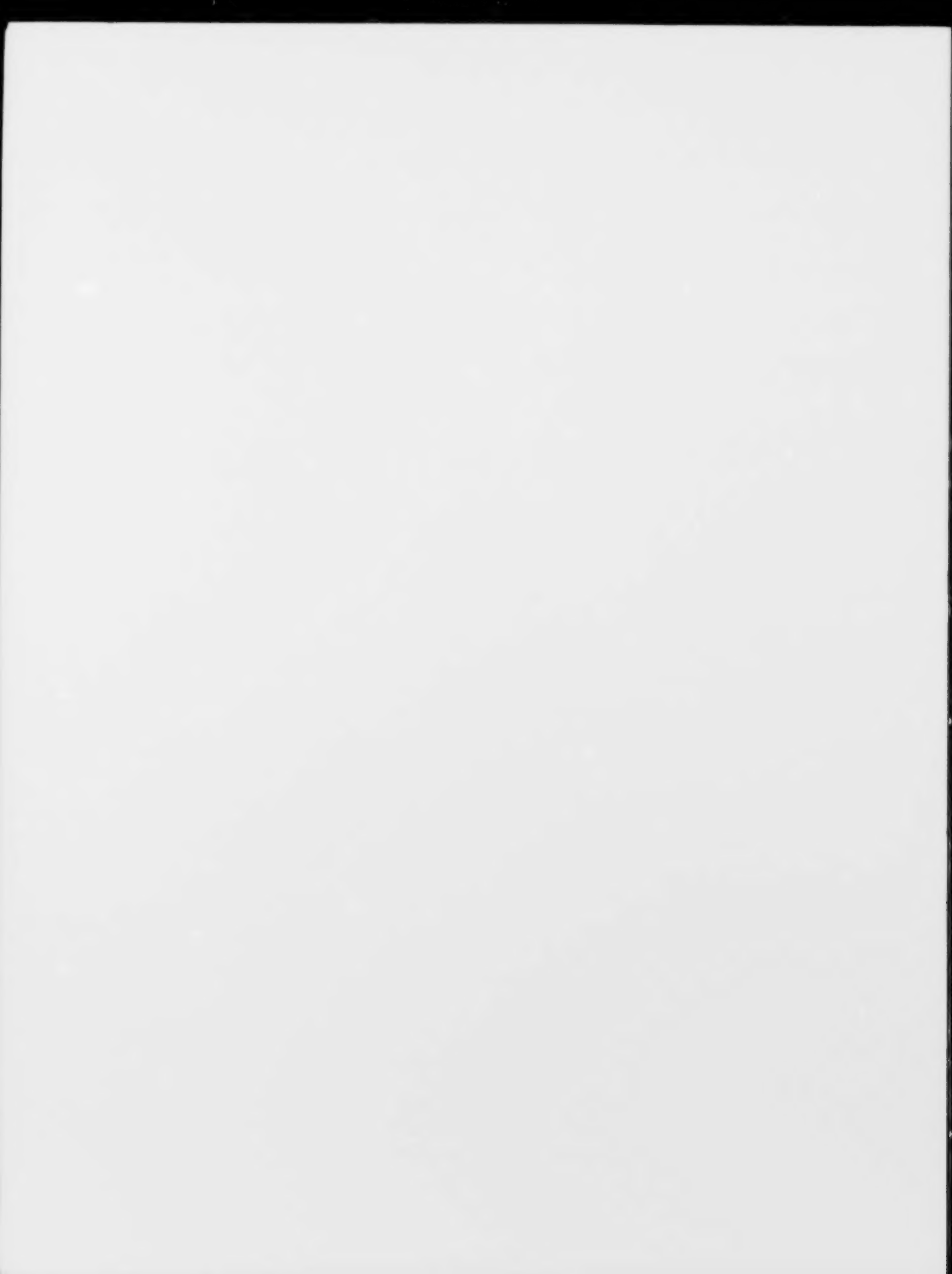


Complex Stand Structures and Associated Dynamics: Measurement Indices and Modelling Approaches

Popular Summaries





Complex Stand Structures and Associated Dynamics: Measurement Indices and Modelling Approaches

Popular Summaries

Compiled by

P. F. Newton and V. M. LeMay, conference cochairs

with A. Groot, P. Marshall, W. Meades, K.O'Hara, M. Sharma and M. Ter-Mikaelian

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Abstract

Complex forest stands that have resulted from paradigm shifts in forest management practices (e.g., variable retention silvicultural systems, natural disturbance pattern emulation, systematic/selection mechanized thinning treatments) represent an increasing proportion of the productive forest land base throughout many of the world's forested ecosystems. Characterized by structural heterogeneity (e.g., multimodal diameter, height, and age distributions with aggregated and segregated spatial patterns), complex stands are intrinsically difficult to measure and model, particularly their structural attributes (e.g., size distributions and spatial patterns) and temporal dynamics (e.g., survivor growth, ingress (regeneration), mortality, succession vectors, and spatial dynamics).

In response to this analytical challenge, discussions were initiated with various members of the regional (Ontario Forest Research Institute), national (Canadian Forest Service), and international (Units 4.01.02 (Growth models for tree and stand simulation), 4.01.00 (Forest mensuration and modelling), 4.01.03 (Instruments and methods in forest mensuration), and 1.05.00 (Uneven-aged Silviculture) of the International Union of Forest Research Organizations (IUFRO)) forest science and management communities. The resulting consensus was the need to benchmark the current state of knowledge, share successes, and compare various measurement and modelling approaches via an international scientific conference. Thus, this conference, entitled *Complex Stand Structures and Associated Dynamics: Measurement Indices and Modelling Approaches*, was organized with the overall purpose of reviewing the latest measurement and modelling research pertaining to complex stand structures from a global perspective. The consequences of managing complex stand structures in terms of the operational logistics, product quality and value outcomes, and economic implications, were important secondary considerations.

The conference program included six plenary sessions, concurrent poster sessions, and a field tour to view some of the complex stand structures common to the Great Lakes–St. Lawrence Forest Region of central Canada. Plenary sessions consisted of a state-of-knowledge overview related to the session theme by an invited keynote speaker, followed by volunteer oral presentations. Sessions themes were: *Overview of Complex Stand Structures*, *Dynamics of Complex Stand Structures*, *Measuring Complexity I*, *Measuring Complexity II*, *Modelling Complexity*, and *Managing Complex Stand Structures: Economic Consequences, Operational Challenges, and Decision-support Tools*, with respective keynote addresses by Jerry Vanclay (Southern Cross University, New South Wales, Australia), Kevin O'Hara (University of California (Berkeley), California, USA), Arne Pommerening (University of Wales, UK), Bruce Larson (University of British Columbia, British Columbia, Canada), Harold Burkhart (Virginia Polytechnic Institute and State University, Virginia, USA), and James Goudie (Research Branch, Ministry of Forests, British Columbia, Canada). An invited summary of all oral and poster presentations was provided by Hubert Sterba (University of Natural Resources and Applied Life Sciences, Vienna, Austria).

This document provides a brief, detailed summary of each presentation in three-page popular summary format. Specifically, short, unedited syntheses were supplied by each author that summarize the essential information of the underlying research study, including scope, objectives, methods, results, inferences, and major conclusions. The primary purpose is to document the research studies presented for the benefit of the forest science and management communities and foster onsite discussion among conference participants. Following successful peer review, a subset of these studies will be published in a special issue of the journal *Forestry* (Oxford University Press), planned for release in 2008.

Resumé

Les peuplements forestiers complexes qui sont le résultat de changements de paradigme survenus dans les pratiques d'aménagement des forêts (p. ex., régimes de coupes à rétention variable, émulation de perturbations naturelles, traitements d'éclaircie mécanisée systématique/jardinatoire) représentent une proportion croissante du terrain forestier productif dans un grand nombre des écosystèmes forestiers du monde. Caractérisés par leur hétérogénéité structurelle (p. ex., distributions plurimodales des diamètres, des hauteurs et des âges selon des profils spatiaux globaux et distincts), les peuplements complexes sont intrinsèquement difficiles à mesurer et à modéliser, particulièrement en ce qui a trait à leurs attributs structurels (p. ex., distributions en dimensions et profils spatiaux) et à leur dynamique temporelle (p. ex., croissance de peuplement, entrée [régénération], mortalité, vecteurs de succession et dynamique spatiale).

En réponse à ce défi analytique, des discussions ont été engagées avec divers membres des milieux des sciences et de l'aménagement forestiers sur les plans régional (Institut de recherche forestière de l'Ontario), national (Service canadien des forêts) et international (unités 4.01.02 [Growth models for tree and stand simulation], 4.01.00 [Forest mensuration and modelling], 4.01.03 [Instruments and methods in forest mensuration] et 1.05.00 [Uneven-aged Silviculture] de l'Union internationale des instituts de recherches forestières [IUFRO]). Selon le consensus obtenu, il s'avérerait nécessaire d'effectuer une analyse comparative de l'état actuel des connaissances, de faire part des réussites et de comparer plusieurs méthodes de mesure et de modélisation au cours d'une conférence scientifique internationale. Cette conférence, intitulée *Complex Stand Structures and Associated Dynamics: Measurement Indices and Modelling Approaches*, a donc été organisée dans le but général d'examiner les plus récentes recherches sur la mesure et la modélisation qui se rapportent aux structures de peuplement complexes d'un point de vue mondial. Les conséquences de la gestion des structures de peuplement complexes, en ce qui concerne la logistique opérationnelle, les résultats de qualité et de valeur des produits, et les implications économiques, constituaient d'importantes considérations secondaires.

Le programme de la conférence comprenait six sessions plénières, des présentations simultanées par affiches et une visite sur le terrain pour voir certaines des structures de peuplement complexes qui sont répandues dans la région forestière des Grands Lacs et du Saint-Laurent au Canada central. Au cours de chaque session plénière, un conférencier d'honneur a offert une vue d'ensemble de l'état des connaissances en rapport avec le thème de la session, ce qui a été suivi de présentations orales volontaires. Les sessions se sont déroulées sur les thèmes suivants : vue d'ensemble des structures de peuplement complexes, dynamique des structures de peuplement complexes, complexité de la mesure I, complexité de la mesure II, complexité de la modélisation et gestion des structures de peuplement complexes : répercussions économiques, difficultés opérationnelles et outils d'aide à la décision, avec des discours-programmes prononcés respectivement par Jerry Vanclay (Université Southern Cross, Nouvelle-Galles du Sud, Australie), Kevin O'Hara (Université de la Californie [Berkeley], Californie, États-Unis), Arne Pommerening (Université du pays de Galles, R.-U.), Bruce Larson (Université de la Colombie-Britannique, Colombie-Britannique, Canada), Harold Burkhart (Virginia Polytechnic Institute and State University, Virginie, États-Unis) et James Goudie (direction générale de la recherche, ministère des Forêts, Colombie-Britannique, Canada). Hubert Sterba (University of Natural Resources and Applied Life Sciences, Vienne, Autriche) a fait un résumé de toutes les présentations orales et présentations par affiches.

Le présent document contient un bref exposé détaillé de chaque présentation, sous la forme d'un résumé populaire de trois pages. Plus précisément, chaque auteur a fourni une courte synthèse non révisée qui reprend en peu de mots l'information essentielle contenue dans l'étude sous-jacente, y compris le cadre, les objectifs, les méthodes, les résultats, les inférences et les principales conclusions de l'étude. Le but premier consiste à décrire les études de recherche présentées à l'intention des milieux des sciences et de l'aménagement forestiers, ainsi qu'à favoriser la discussion sur place, parmi les participants à la conférence. Suite à un examen confraternel, un sous-ensemble de ces études sera publié dans un numéro spécial de la revue *Forestry* (Oxford University Press), numéro qui devrait paraître en 2008.

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We thank keynote speakers **Jerry Vancley** (Australia), **Kevin O'Hara** (USA), **Arne Pommerening** (UK), **Bruce Larson** (Canada), **Harold Burkhart** (USA), and **James Goudie** (Canada) for their state-of-knowledge overviews. The contributions of **Andreas Zingg** (Austria) as session moderator and **Hubert Sterba** (Austria) as invited summary speaker were very much appreciated. We also thank all the regional, national, and international participants for their individual contributions and insight, which collectively resulted in a very informative and successful conference.

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The organizing committee consisted of: (1) co-chairs **Peter Newton** (coordinator, IUFRO Unit 4.01.02/CWFC, Canadian Forest Service (CFS), Natural Resources Canada (NRCan)) and **Valerie LeMay** (coordinator, IUFRO Unit 4.01.02, Faculty of Forestry, University of British Columbia (UBC)); (2) scientific committee members **Art Groot** (CWFC, CFS, NRCan), **Ivo Kupka** (deputy coordinator, IUFRO Unit 4.01.02/Czech University of Agriculture), **Peter Marshall** (deputy coordinator, IUFRO Unit 4.01.03/Faculty of Forestry, UBC), **William Meades** (director, GLFC, CFS, NRCan), **Kevin O'Hara** (coordinator, IUFRO Unit 1.05.00/University of California-Berkeley), **Mahadev Sharma** and **Michael Ter-Mikaelian** (OFRI, OMNR); (3) technology transfer staff **Lisa Buse** (popular summary lead and OFRI tour guide; OFRI, OMNR), **Mark Primavera** (web designer and conference photographer; GLFC, CFS, NRCan), **Guy Smith** (media relations lead and GLFC tour guide; GLFC, CFS, NRCan), and **Jason Langis** (tour booklet lead; GLFC, CFS, NRCan); and (4) logistics team members **Joyce Beam** (registration; CEC-FRP), and **Jeff Fera** (registration kits and poster lead; CWFC, CFS, NRCan). Over the last two years, these dedicated members have contributed their valuable time, expertise and assistance to make this conference a reality.

Peter Newton and Valerie LeMay

Conference Co-chairs



**Overview of
Complex Stand
Structures**

Complex Stand Structures: Measures and Models, Paradigms and Prospects

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Introduction

The challenge offered to me was to present a global review of modelling for forest management. A few years ago, this may have been possible, but exponential growth in the number of publications relating to forest modelling means that this is no longer feasible. So instead of a comprehensive census of past achievements, I'm going to offer a biased sample of future possibilities, specifically with respect to measurement and modelling of complex stand structures.

The conference announcement outlined that *complex stand structures* are characterized by vertical, horizontal and spatial heterogeneity that hampers estimation and modelling of temporal dynamics, often exacerbated by changes in forest management that erodes the utility of historic resource monitoring data. This leads to a situation familiar to many tropical foresters: a paucity of data and a plethora of species that may preclude age-based modelling and stratified sampling approaches. Models for tropical rainforests may offer some insights for useful modelling approaches, but the utility of these approaches depends on the local context, so it is important to review current imperatives in forest management.

New Directions in Forest Management and Forest Modelling

Most of us are familiar with many of the current influences on forest management:

- declining cut of large old-growth trees, replaced by young regrowth and industrial plantations;
- less reliance on government forests, more on private industrial and non-industrial owners;
- fewer vertically-integrated operations, with lumber increasingly seen as a commodity;
- growing demands for growers to demonstrate sustainability, and to gain certification; and
- demands for more stakeholders to be involved in planning and overseeing forest operations.

These influences appear to be global and generic, but there are also regional influences: in Europe towards adoption of nature-based forest management in both natural and planted stands, and in Australia (and

many other former European colonies) towards the phasing-out of native forest harvesting and a reliance on plantations, preferably of mixed indigenous species. I offer no value judgements regarding these trends, and merely observe that these influences reflect the emerging expectations of many forests and foresters.

In parallel with these changes in society and forest management, technological changes also exert a strong influence on modelling endeavours. For decades, modellers were hampered by technological limitations, and much effort was invested in making models more compact or efficient. Technological advances have removed most of these limits, so that models now tend to be limited by innovation, rather than by the limitations of computing hardware or software. Comparable progress with remote sensing means that it may soon be more efficient to undertake a forest census using lidar, rather than to sample using ground-based inventory. A forest census obtained efficiently with a remotely-controlled drone would provide geo-referenced height and crown data that could rekindle interest in spatially-explicit models based on height and crown parameters. For decades, we've based yield predictions on small, precise samples, and scaled these estimates up to the stand and estate level. There is little doubt that this remains a good approach for uniform industrial monocultures (but note that agriculture relies increasingly on frequent high-resolution remote-sensing), but does it remain a useful approach for more complex forests when an alternative – to census and simulate every individual tree – is technologically feasible? I've not seen an error budget contrasting these alternatives for complex forests, but guess the answer hinges on whether 'complex stand' is an oxymoron. If the distribution of trees in a forest is such that we can define stands and representative samples within those stands, then the traditional approach will probably continue to serve us well. However, complications in identifying stands and representative samples may indicate that it is timely to consider to a new approach. A series of examples illustrates situations in which traditional measurements and models have been unhelpful, and in which a new approach may be more insightful.

Challenges With Plantations

The area of forest plantation in Australia has increased greatly during the last few years, a result of government policies to reduce native forest harvesting and stimulate plantation investment. There are diverse consequences associated with this expansion: community concerns about land use and livelihood changes, about water use by plantations, and about the viability of new plantings on non-traditional sites. Heterogeneity, unfavourable soils and pestilence at these new frontiers have fuelled a discussion about polycultures, and whether they can increase yields and reduce risk to investors. Simulation studies suggest greater productivity, especially when mixtures include leguminous trees on nitrogen-deficient sites, but industry has been slow to adopt these polycultures. Clearly, a stand-alone simulation is not sufficient to initiate uptake, and greater effort is needed to stimulate change.

Australia has suffered a seven-year drought, and this has made many communities suspicious of plantations that may use more water than the pasture that they replace. Despite this concern about water and the threat of increased regulation, models of plantation water use tend to be simplistic. The Penman-Monteith equation reveals that much of the water may be transpired during a few days of arid winds, but little effort has been invested in designing aerodynamically-efficient decoupled forest canopies. Plantation establishment guidelines often prescribe fire- and stream-breaks that fall short of their objectives and create turbulence that exacerbates transpiration. More sophisticated 'wall-to-wall' spatial modelling may be needed to resolve these issues of water use.

Native Forests and Biodiversity

A popular perception amongst many Australians is that native forests should not be managed deliberately, and that natural processes should prevail. Sadly, fragmentation means that many natural processes no longer function satisfactorily, and that 'benign neglect' may not lead to a good outcome. One example of this is forest decline known as bell miner associated dieback (BMAD) that often occurs when the bell miner, a small but strongly territorial bird, dominates a forest. The proximate cause of decline appears to be an insect (psyllid) outbreak favoured by the territorial behaviour of the bell miners, but the underlying reason appears related to the vertical structure of the forest, and lidar has been useful for mapping stands at risk of BMAD. Existing forest growth models have been unable to offer useful insights for the management

of BMAD, and more sophisticated modelling of stand structure (and possibly of faunal interactions) appears necessary to deal with this issue.

The structural diversity of forests is also pivotal in current discussions about faunal biodiversity. Biodiversity has become a topical issue, and stronger regulation of private native forestry is imminent in several Australian states. Several uni-dimensional indicators of structural diversity have been proposed ('biometric', habitat hectares), but field tests suggest that they are inadequate and that more sophisticated concepts of spatial and temporal variation within forests are needed to advance the discussion surrounding wise forest management in Australia.

People and Forest Dynamics

The shortcoming in the present debate surrounding biodiversity and forest management may be an inadequate understanding and comprehension of forest dynamics. Foresters are trained to think at the landscape-scale, over the long term, but not all nature-lovers share this skill, and opportunities to develop a shared understanding of these insights are often limited. Several success stories from Africa attest to the utility of participatory modelling and other systems thinking approaches in helping communities to develop the understanding needed to engage in an informed debate and collectively devise new pathways towards sustainability. Forest modellers have many of the skills to facilitate such participatory modelling, but one of the challenges is to represent complex processes with simple constructs that are easily communicated. Visual modelling environments such as Simile help to make modelling accessible, but inspired leadership is also necessary to guide participants towards models that are both accessible and sufficient. Current research may offer new insights about processes and representations that facilitate such collaboration.

Future Challenges

During the past decade, much effort has been directed at the 'micro-scale', towards better physiological and single-tree models. Changing paradigms of forest management may stimulate a revival of models at the 'meta-scale', so that we can better deal with the complexity created by greater diversity in spatial and temporal structure of forests, and in the needs and demands of forest managers and stakeholders. The biggest challenge is to create models that are reliable yet accessible and understandable.

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Silvicultural Systems for Mixedwood Stands in Boreal Forests of Western Canada

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Introduction

While mixtures of aspen and spruce occupy many of the most productive sites and are both prominent and ecologically important components of the boreal forests of western Canada experience with intentional management of these stands is limited. Mixedwood stands comprise a broad range of proportions of the two component species as well as a range of vertical and horizontal structures. Following stand replacing disturbances (e.g., wildfire or clearcutting), aspen dominates regenerating stands for 60 years or longer. Young stands with moderate or high aspen densities are identified as aspen stands with a spruce understory. Mixedwood stands, where spruce occurs as a recognizable component in the dominant and codominant tree layers, represent mid to late successional stages. This can make attempts to recreate mixedwood structures immediately following clearcutting expensive and challenging.

Clearcutting With Planting

Aspen can serve as a nurse crop in suppressing understory vegetation development and reducing winter and summer frost injury (where these are factors limiting spruce establishment) during the first 2 to 5 years after planting spruce. As illustrated in Figure 1, spruce growth is reduced by aspen, and this is generally related to the density of aspen. Spruce can also benefit substantially from control of *Calamagrostis*

or other herbaceous vegetation, which is generally less abundant under dense aspen than in openings. Early control of herbaceous and aspen competition can accelerate spruce development and potentially increase spruce yields.

Herbicide treatments (glyphosate, imazapyr) can provide effective control of *Calamagrostis*, but must be used selectively since they also reduce aspen density and yield. Spot cutting or herbicide treatments, which remove aspen and *Calamagrostis* within a 1 or 2 m radius spot around individual spruce provides substantial improvement in spruce growth, and the aspen growing between treated spots provides protection from winter and summer frost injury. Thinning of aspen can also be used to effectively reduce competition and improve spruce growth (Bokalo et al. 2007), however it is difficult to control the herbaceous layer under uniformly spaced aspen.

Treating patches or strips with suitable herbicides provides an opportunity to control both aspen and herbaceous competition and will lead to creation of horizontal structure. Aerial application of herbicides may be possible and could substantially reduce tending costs compared to selective ground-based treatments. To maintain a mixedwood structure, treated patches must be kept to reasonable sizes. Voicu and Comeau (2006) suggest that spruce patches whose width is 0.6 to 1.0 times the aspen tree height should provide excellent conditions for spruce growth (Figure 2).

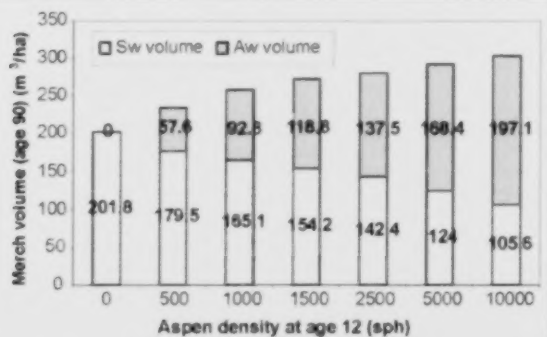


Figure 1. MGM 2007a simulations of effects of aspen (Aw) density on yield of a stand planted with 1000 spruce (Sw SI50=18 m, Height at age 12=1.9 m; Aw SI50=20 m, Height at age 12=6.3

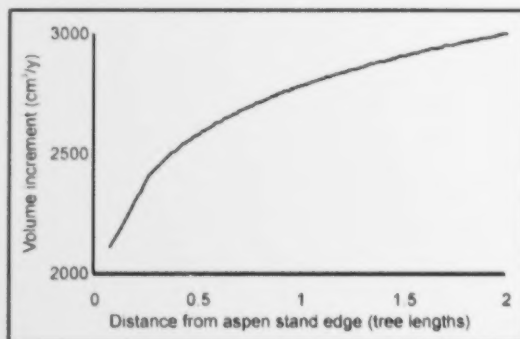


Figure 2. Relationship between spruce growth and distance from the edge of 12-year-old aspen stands (after Voicu and Comeau 2006).

To take advantage of the successional nature of mixedwoods, and of the shade tolerance of white spruce, aspen can be removed in a commercial thinning of a planted but untended stand between ages 50 and 70, which will release understory white spruce. Subsequently, a white spruce dominated mixedwood stand should be ready for harvest 60 to 80 years in the future (about 120 years after planting). A variation on this approach is to plant spruce under stands of aspen between ages 30 and 50, followed by removal of the aspen 20 to 30 years later when the spruce are more than 4 or 5 m tall. Underplanting in closed canopied aspen stands works well, and success is not usually improved by site preparation or brushing treatments. However snowshoe hare browsing of underplanted spruce seedlings can be a problem (Comeau et al. 2004).

Shelterwood and Selection Systems

Natural regeneration of white spruce has been found to be inconsistent and unreliable in clearcuts and spruce seed trees are generally not wind firm. Scattered mature white spruce in natural stands

provide seed for regeneration and suggest opportunities for use of shelterwood systems and selection systems (Stewart et al 2000). The key to successful use of natural regeneration of white spruce in the understory of aspen stands is disruption of the forest floor and the understory vegetation. Maintaining the aspen component under shelterwood or selection systems requires creating openings which are large enough to be conducive to abundant suckering and growth of this shade intolerant species (Frey et al. 2003). Strip and patch shelterwoods and group selection systems have been shown to be effective.

Yield and Cost Implications

Further discussion of these and other approaches are provided by Lieffers et al. (1999) and Comeau et al. (2005). As Figure 1 and Table 1 illustrate, mixedwood stands can provide greater total yield than single species stands. Cost implications, and different end uses and values of spruce and aspen must also be considered (but are beyond the scope of this summary).

Table 1. Yield implications of seven silvicultural systems in boreal mixedwood stands (based on simulations using MGM2007a).

			1. Aspen (At)	2. White spruce (Sw) - 1100 sph	3. Planted and thinned mixedwood	4. Plant and CT	5. Plant, PCT, and CT	6. Patches: Sw - 60%, At - 40%	7. Underplant
Establishment.			At natural regen	Plant 1100 Sw	At natural regen, Plant 1100 Sw	At natural regen, Plant 1100 Sw	At natural regen, Plant 1100 Sw	At natural regen, Plant 1100 Sw	At natural regen
Veg. Mgmt				Herbicide	Spot brushing	Spot brushing	Spot brushing	Herbicide 60%	
Precommercial thin (PCT)					1500 Aw		1500 Aw		
Underplant									1100 Sw at age 40
Commercial thin (CT) (age)						60	60		60
Final Harvest Age			60	100	140	140	140	100	140
Volume Harvested		At CT				163.6	90.0	78.4	194.0
MAI (m³/ha/y)	At	Final	196.0	?	119.0	0.0	21.6	138.5	50.0
	Sw	Final		230.8	183.0	239.1	255.3		204.0
	Total		196.0	230.8	302.0	402.7	366.9	215.9	448.0
	At		3.3		0.9	1.2	0.8	0.8	1.7
	Sw			2.3	1.3	1.7	1.8	1.4	1.5
	Total		3.3	2.3	2.2	2.9	2.6	2.2	3.2

Conclusion

While there are a diversity of approaches available for creation and management of boreal mixedwood forests, appropriate silvicultural systems must be employed and planning is required in order to maintain a desired variety of successional mixedwood stand types at the forest/landscape level. A better understanding of how different practices influence species and structural diversity at both the stand and forest level, and stand level yields is needed to provide better linkage between silvicultural systems, crop plans and management objectives.

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Characteristics and Modelling Challenges of Irregular Forests in Southeastern Australia

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Introduction

Various types of eucalypt forests constitute major native forest resources of Australia, which cover about 77% of national forested areas (BRS 2007). In the southeastern coasts (including Tasmania), where rainfall is relatively high, the lowland mixed species eucalypt forests are extensive. For example, approximate 78% of the public land of Victoria is covered by the lowland mixed species eucalypt forests, which occur below 700 m elevation on the eastern foothills and coastal plain. Two main species groups are identified (the messmate-peppermint-gum and silvertop-stringybark groups), which are represented by major commercial species of *Eucalyptus obliqua*, *E. radiata* and *E. viminalis*, or *E. sieberi*, *E. globoidea* and *E. baxteri* respectively. Early utilization of these forests was primarily selective logging, the resultant stands were often patchy, mixed-age, with substantial levels of defective old trees. As the demand for timber and forested areas reserved for conservation increased, more intensive logging was applied. Currently, practice includes clearfell, and deliberate retention of defective mature trees (overwood) during logging to provide habitat for wildlife and seed for regeneration, patches of regrowth with growth potential may also be retained. The areas are also some of the most fire-prone areas in the world; wildfires periodically sweep through the area so that dense patches of regrowth varying ages are characteristic of these forests (Lutze *et al.* 1999). The structure of these forests is highly variable with both uneven-aged and even-aged stands common as a result of fire and logging history.

Stand dynamics information and models for analyzing the alternative management options are urgently required by forest management for the mixed forests. Modelling challenges include accurately estimating site productivity and quantifying the suppressive effects of retained overwood and forested edges on regeneration and development of these forests. In this study, these issues were preliminarily investigated using the data from a range of mixed forest studies in Victoria. The aims were to improve the understanding

of regeneration and early development of these mixed forests under different silvicultural systems and a range of retained overwood levels and gap sizes.

Materials and Methods

Data

Three data sets provided by Victorian Department of Sustainability and Environment were used in this study, including: (i) tree growth and survival data from permanent plots of a large-scale silvicultural experiment established in the lowland mixed forests to evaluate a range of harvesting treatments, including group selection with 0.03, 0.25 or 1-ha gaps, small 4- or 10-ha clearfells, seed tree (5 retained trees ha⁻¹, about 7% retained basal area), and the shelterwood systems with 22% or 35% retained basal area, these treatments were also compared to unharvested control (*i.e.* 0 ha gap or 100% overwood retention). (ii) tree species, crown, diameter and height data taken in an edge effect study from sixteen 50m x 5m transects established in the 4-ha clearfell treatment of the above experiment, and (iii) Inventory data (tree, stand and environmental variables) from 1306 variable-radius plots and 582 fixed-area plots sampled across the lowland mixed forests in Gippsland, Victoria.

Analysis

The experimental and edge effect study data provided opportunity of analyzing the suppressive effects of retained overwood (*i.e.* data from clearfells, 7, 22, 35 and 100% retained basal areas) and forested edges (*i.e.* data from 0, 0.03, 0.25, 1-ha gaps, and 4- and 10-ha clearfells) on regeneration and early development of regenerated stands. Germination and seedling density at age 3 y were first examined with analysis of variance, and the relationship between these regeneration measures and mean distances from the plots to the nearest retained trees were modeled. Overwood and edge effects were also evaluated for stand density and growth at age 10 or 12 y. To investigate the appropriate measures for site productivity, stand attributes estimated for the inventory plots, particularly

merchantable volumes and basal areas, were related to a range of stand attributes (e.g. site index, species composition) and environmental variables.

Results

Some preliminary results are summarized as follows.

Site Productivity

The dominant height-based site indices appeared to be still appropriate for measuring the site productivity of these mixed stands. A range of environmental variables was found to be useful for improving the prediction of dominant height. In general, dominant height was positively related to bioclimatic (rainfall) and terrain variables (elevation) and negatively related to radiometric (annual radiation) variables.

Overwood Effects

All harvesting treatments tested resulted in a satisfactory level of site occupancy, but 10-ha clearfell was the lowest. Distance from the nearest retained overwood had not effects on seedling density at age 3 y. However, diameter and height growth of regrowth were reduced as increasing retained overwood and decreasing gap size. Basal area and volume increased with increasing gap size and decreasing retained overwood.

Edge Effects

Similar to the responses to overwood effects, regeneration was established successfully under the entire range of harvesting treatments tested. However, forested edges had a severe suppressive effect on regrowth. Thus suppressive effects were statistically significant to 5 m for dominant height, 13 m for mean diameter, and 26 m for basal area. Edge effects also varied with crown class, species tolerance for a given distance from the forested edge.

Species Composition

All treatments showed a significant shift in species composition of regrowth in favor of *E. sieberi*, but the 7% overwood retention and clearfell treatment were less pronounced. However, this might have been the combination of seed supply and competition effects.

Discussion

Preliminary results of this study were consistent with other studies, which found the lowland mixed species eucalypt forests in southeastern Australia can be

regenerated reliably relied on natural seed sources (e.g. Lutze *et al.* 1999). Therefore, seed tree system comprising 5 – 9 retained mature trees ha⁻¹ is most appropriate for these forests. However, the retained overwood and forested edges had a significant suppressive effect on the regrowth development, and the long-term impacts of thus suppressive effects on future yield need to be further investigated.

The traditional site index appeared to be appropriate for estimating site productivity of these mixed forests. However, this result may be due to the fact that wildfires frequently sweep through the areas so that patches of fire regrowth were relatively even-aged, and previous inventories have been focused on the mixed stands having a recent fire or logging history only. Further study is needed to develop models for improving dominant height prediction and accounting for the variation of environmental conditions, the suppressive effects of retained overwood and forested edges. For this, a mixed-effect model approach, such as that used by Wang *et al.* (2007) can be superior to the conventional regression models.

Conclusion

The study concluded that the regeneration of lowland mixed species eucalypt forests in southeastern Australia can be established successfully under a wide range of gap sizes for group selection and retained overwood levels for seed tree system. However, the survival and development of regrowth were subject to the suppressive effects of retained overwood and forested edges. New growth models are required for yield prediction with accounting for the long-term effects of overwood retention under these management practices for the mixed species eucalypt forests.

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Structural Dynamics of Boreal Conifer Stands: Mixed Natural vs. Plantations

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Introduction

Over 1 million hectares of Ontario's managed boreal conifer forests have been regenerated to conifer plantations in the last 10 years alone, consisting mainly of black spruce (*Picea mariana* [Mill.] B.S.P.) and jack pine (*Pinus banksiana* Lamb.). The gross volume of managed jack pine plantations is close to 600 million m³ (Guo and Wang 2005). While establishment is costly, plantations are thought necessary to maintain the conifer wood supply, since portions of the productive landscape have been set aside for other values (Bell *et al.* 2000). To evaluate whether these plantations will be able to provide significant contributions to Ontario's wood supply in the near future, there is a need to better understand their structural dynamics and growth potential. Current models used to predict their yields are largely based on measurements made in natural origin stands (Payendeh and Wang 1995).

We sought to compare stand development patterns and productivity in natural stands and managed plantations. Our focus was on whether intensive management of boreal plantations can be expected to result in enhanced fibre yield and/or reduced age to operability. We also examined the potential of managing for both species in a mixedwood as a means to meet demands for wood in the short-term (*i.e.*, commercial thinning, compositional treatment) in addition to the final rotation age. Enhanced long-term forest productivity through alternatives to traditional monoculture plantations, like this, is predicated on niche separation between tree species in mixedwood forests.

Approach

Mensurational data from fixed-area plots were collected from 21 plantations (14 jack pine (Pj); 7 black spruce (Sb)) ranging in age from 6-53 years, and 25 fire origin conifer-dominated stands (age 5-125 years). The plantations were established on rapidly-drained, moderately-fresh (MR = 1), fine deltaic sands, overtopped by a silty, very fine sand loess cap. Of the fire-origin stands included in this study, fifteen were

situated on rapidly-drained, moderately dry (MR = 0) outwash sands. The remaining 10 natural stands were situated on coarse loamy, morainal tills. Soil profile development on these sites was indicative of weakly-developed Orthic Humo-Ferric Podzols, with a poorly-defined elluvial layer (Ae₁ - Ae) and a moderately thick (20-30 cm) Bf₁ - Bf horizon.

Standard mensurational measurements (*e.g.* total height, dbh, crown class) were taken on both living and standing dead trees. Stem analysis data from 46 Sb trees from the mature stands (age = 115 years) was also collected. A generalized 3-parameter modified-Weibull function was used to develop individual tree (height, dbh) and stand-level (density, stand volume) growth curves for both the mixed conifer natural stands and the monoculture pine and spruce plantations.

Stand Dynamics

In natural origin stands, high post fire Pj densities ($\approx 20,000$ stems $\cdot$ ha⁻¹) in young stands experience self-thinning, and by age 60 are reduced in number to near 1800 stems $\cdot$ ha⁻¹ (Figure 1a). Sb recruitment occurred over a much longer period, and constituted $\sim 46\%$ of stand density after 5 decades, occupying low- and mid-canopy positions. Longer-lived Sb became increasingly dominant in older stands due to mortality of self-thinning Pj. Sb occupies more growing space in older stands (data not shown), which exhibited a somewhat normal distribution of diameters after 80+ years. In plantations, the growing space is more evenly distributed through uniform spacing at establishment. As a result both Sb and Pj exhibit a normal diameter distribution 5 decades after establishment (Figure 1b).

The tree recruitment period lasts considerably longer in natural origin stands, and is dominated by Pj ($\sim 90\%$ of established trees at age 23; Figure 2). Natural high density stands experience a high rate of mortality, as older stands tended to have less than 5000 stems ha⁻¹. Plantations, on the other hand, tended to maintain their establishment density (~ 3000 stems ha⁻¹) with relatively low rates of mortality. The model predicts stand densities to approach 1000 sph by age 80 in both Pj and Sb plantations.

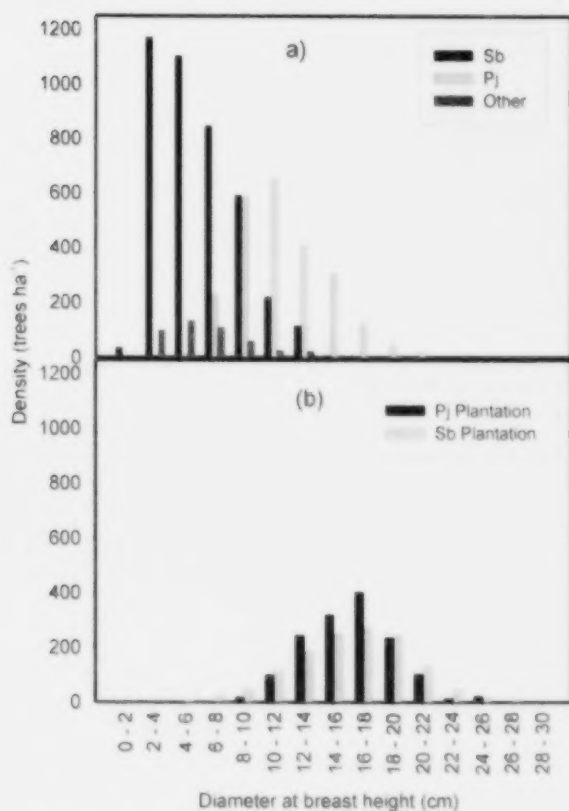


Figure 1

Productivity

In the first 10 years after establishment, height growth in both the Pj and Sb plantations largely followed that documented for the natural stands (Figure 3). After this, high densities and rapid crown closure in the natural stands resulted in intense competition, poorer individual tree performance, and in increased deviation in the height curves compared to the plantations.

At age 50, the natural stands were averaging 210 m³ ha⁻¹ in GTV, but there was considerable variability due to variation in stand composition, density, and productivity. Though there were changes in diameter distribution and species composition with age, very little net increase in stand volume occurred after

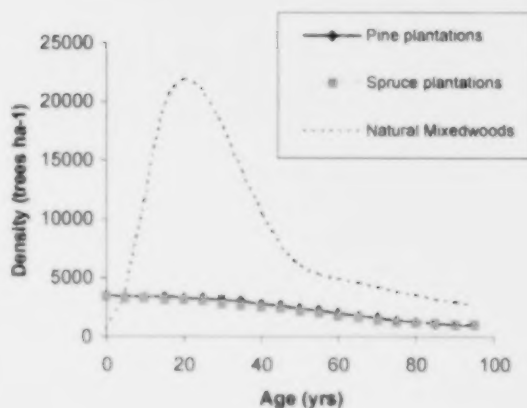


Figure 2

age 65, peaking at approximately 300 m³ ha⁻¹. Both the individual tree and stand-level parameters were comparable to Plonski's site class II values. The lack of density regulation (*i.e.*, high initial densities followed by an extended, inefficient self-thinning period) represented one of the important factors that may have reduced realized wood fibre productivity in these natural, mixed-conifer stands.

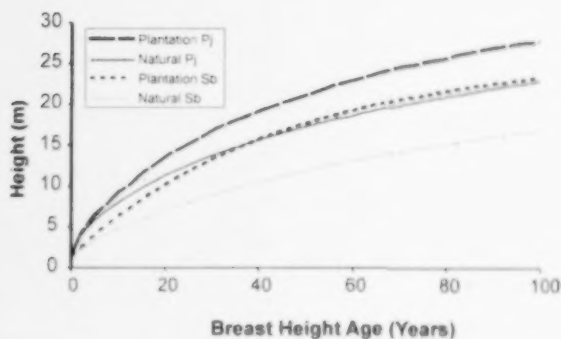


Figure 3

The density-regulated plantations, on the other hand, consistently outperformed the natural stands based on all measured individual and stand-level parameters, and significantly lowered the age to operability. For example, GTV age 50 was $272 \text{ m}^3 \cdot \text{ha}^{-1}$ and $307 \text{ m}^3 \cdot \text{ha}^{-1}$ for the jack pine and black spruce plantations, respectively. Based on the high PAI values in these plantations (Figure 4), compared to their natural stand counterparts, it is anticipated that stand volumes will continue to increase beyond the peak reached in the natural stands at age 65.



Figure 4

In terms of site index (height at base age 50), both plantations types exceeded the expected heights for Plonski's site class I. The black spruce, in particular, was nearly 4 m taller at age 50, and was carrying double the stand volume.

Management Opportunities

Potential approaches and associated benefits associated with mixed conifer management (e.g., mixed species plantings, multi-entry cutting systems) will be discussed.

Complex Stand Development and Management in BC's Boreal Forest

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Introduction

Complex ecosystems function within a variety of diversity measures including structural and functional diversity from stand to landscape levels (Kimmins 1997). Because of the array of mixedwood stand types, little is known about their dynamics but lower yields have been attributed to them (Assmann 1970). As a result, aggressive vegetation control has been justified to enhance forest productivity (Wagner et al. 2001, 2006). Current free growing standards in British Columbia (BC) stipulate crop trees must be free of competing vegetation to maximize productivity (Anonymous 2002). This is often achieved at great economic cost, with additional costs to landscape level diversity and stand structure, and poses a potential threat to the stability and resilience of forests (Simard and Vyse 2006).

More recent literature suggests yields may be greater in mixed species stands than in pure stands (Simard et al. 2005; Kelly 2006). Over a rotation, mixed species stands may yield greater wood volume than a single-species stand and provide other stand-level benefits (Man and Lieffers 1999). In an FVS (Lakes States Version) (Miner et al. 1988) modeling exercise for Fort Nelson prior to data collection, projections suggested spruce yields will be greater in spruce – broadleaf (birch) mixtures than in pure spruce stands; counter to current guidelines.

This project seeks to further our understanding of the dynamic interactions between conifer crop trees (spruce) and associated broadleaf (paper birch or aspen) competition in the boreal forests of north eastern BC. The primary objective is to define broadleaf thresholds deleterious to long term productivity, diversity, and health and to minimize operational costs.

Materials and Methods

Temporary sample plots (TSP) were installed on sites in the Fort Nelson (~58° N latitude) and Fort St John (~56° N latitude) timber supply areas to collect data of species-density relationships across a range of early stand conditions and ages. Growth of spruce was measured under varying densities of birch (Fort Nelson) or aspen (Fort St John).

Tree lists were generated from the TSP data for Fort Nelson (spruce/broadleaf sph, None – 1200/0 sph, Mid 1200/3333 sph, High 1200/7333 sph) and Fort St John (Low – 1200/450 sph, Mid – 1200/3680 sph, High 1200/7010 sph) density treatments. Tree lists were run in SORTIE-ND (2006) as a mixed species stand and then again with all the broadleaf stems removed (brushing) for 100 years from today. Two brushing regimes were used for economic assessment, aerial application of the herbicide Glyphosate® and manual brushing. Both treatments are used operationally. Planned rotation age (PRA) in Fort Nelson is about 85 – 90 years while in Fort St John it is 80 – 85 years. TIPSy (Mitchell et al. 1992) bare ground projections were done for spruce at SI_{50} = 18, 21 and 24 m.

Net present value (NPV) was determined for each scenario. Economic assumptions are presented in Table 1. Sensitivity analyses were conducted. Recommendations are based on NPV findings at PRA.

Results

At Fort St John (FSJ), yield was reduced at Mid and High broadleaf densities compared to the Low but there was no difference between Mid and High yields. Brushing enhanced spruce growth at Mid and High densities but not Low. At Fort Nelson (FN), spruce yield was reduced by retaining the broadleaves. Removal of the broadleaves enhanced spruce productivity in FN. The spruce yields observed for the None and Low density treatments at FN and FSJ respectively compare to a projection in TIPSy between 21 and 24 m at SI_{50} .

The best base case NPV at PRA, as expected, at FSJ was the Low density. If chemical brushing were used, the High density NPV was marginally better than the other two densities but not as good as the untreated Low NPV. Manual brushing resulted in better NPV for Mid and High density treatments but not the Low density. If the real interest rate was increased to 4%, the NPV for chemical brushing was better than no brushing which was better than manual brushing. However for the Low density treatment, not brushing was best. Both brushing regimes were favorable at 2%. As we do not encounter stands with x or y deciduous stocking but rather a composite of densities, the NPV from the three density treatments were weighted (Table 1) and a weighted NPV

Table 1. Base economic parameters for Fort Nelson and Fort St John.

Parameter	Fort Nelson (FN)	Fort St John (FSJ)
Real interest rate	3%	3%
Stumpage - conifer	\$30 per m ³	\$30 per m ³
Stumpage - broadleaf	\$10 per m ³	\$10 per m ³
Stumpage inflation	1.4%	1.4%
Plantation establishment	\$1200 per ha	\$996 per ha
Herbicide treatment	\$750 per ha	\$450 per ha
Manual brushing	\$1400 per ha	\$850 per ha
Weighting of stand types	equal	equal

determined. For the base case, chemical and manual brushing were both better than not brushing but at 4%, chemical was best followed by not brushing. If half the area is Low density and rest equally divided between Mid and High densities, chemical is best at 3% but not brushing is best at 4%.

For the base case NPV at PRA in FN, the best NPV was in the None density treatment. At 4% all NPV were negative but again the None density was best. When the areas were weighted, the base case resulted in not brushing being the best management option. This was also the case at 2% while at 4%, all NPV were negative but again not brushing was the best treatment option.

Discussion

In both FSJ and FN, brushing broadleaf species at about 18–21 years post-establishment increased conifer productivity. In FN there was a productivity difference between unbrushed densities, suggesting a competition threshold, while in FSJ, the productivity was similar between Mid and High densities but less than Low. This also suggests competition density thresholds. The SORTIE-ND yield projections were reasonable for the FN scenarios but were optimistic for the FSJ scenarios. The growth and yield module requires refinement. This will result in better information on which to base management decisions.

Economically brushing may be justified in FSJ but the decision depends on whether brushing is a chemical or manual treatment. Often the cost of the manual brushing appears to be unjustified. If chemical treatment is not an option, not brushing similar stand types may be the best investment in FSJ. Generally in FN, it appears that brushing was not warranted even though broadleaves reduced conifer yield. Therefore in many instances brushing may be administrative in FN rather than investments in the future stand (Simard and Vyse 2006).

At both sites, yields were not greater in mixed stands (*c.f.* Simard et al. 2005, Kelty 2006) but the broadleaf threshold exceeded 3000 sph. The early FVS projections suggested an optimum density of

1500 2000 sph. When yields from all scenarios were examined after PRA, yields converged. This suggests not brushing may be a viable management alternative as other benefits will accrue to the stand (Man and Liefers 1999). This is supported by the economic analysis, indicating in some cases, the PRA could be increased. Clearly brushing on complex stands is not a straight forward management decision.

Conclusion

Based on our scenarios, concerns expressed about volume loss in these stands over the rotation due to competition from broadleaf vegetation may be valid but vegetation control may be unwarranted.

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Optimum Stand Structure of Over-Cutting Forest

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Introduction

Over-cutting forest is formed after cutting at an excessive intensity. It is in a form between primary forest and secondary forest. When managed rationally, over-cutting forest can develop into coniferous-broadleaved forest with desirable quality and high yield. However, if being managed irrationally, it can also be degenerated shrubland, even grassland (Xingang Kang et al. 2003). This study was intended to determine the optimum stand structure for over-cutting coniferous-broadleaved forest, namely the state of maximum growth rate of volume, then analyze its structure.

We monitored stand dynamics of forests in Jinggouling Forest Station (Lat. 43°22'N, Long. 130°10'E), Jilin Province for 20 years. The study area is 16286 hm²; forest stock volume is 2062663 m³. The main vegetation type is mixed spruce-*Pinus* coniferous-broadleaved forest. After the establishment of plots, they were re-measured every two years, and measured before and after selective cutting. Some plots were managed with control method.

Material and Method

The study site was in Jinggouling Forest Station on the north slope of Changbai Mountain. It is a multi-storied and uneven-aged forest. Young and middle-

aged trees dominate the forest. Vertically coniferous and broadleaved trees were separated into distinct layers, with spruce (*Picea koraiensis*) and *Pinus* (*Abies nephrolepis*) present in the top canopy and the white birch (*Betula platyphylla*) in the lower layers. The material we used in the study is listed in Table 1.

These plots listed in the table above can represent this kind of ecosystem, according to nearly the same site, cutting density, volume level and et al. to other plots.

Firstly, the stand volume is calculated by plots and by growth season with the volume formula provided by Jinggouling Forest Station, and calculate volume growth rate correspondingly with the formula produced by Pressler. For each site, data were standardized to per hectare values. Then select data with the higher value of volume growth rate (Figure 1). At last, similarities and differences are compared between the average plots and productive plots in several aspects, including species composition, diameter structure, stand density, cutting density, and et al.

Results

After analysis, it was found the diameter structure displayed typical inverse J-shaped curve. It is better to *Pinus* diameter structure with negative exponential distribution and *q* (Zhengzhong Yu and et al. 1996), especially in the plots abundant in small trees.

Table 1. Detail of collective material.

Plot type	Number	Area in all (hm ²)	Established year of plots	Area of each plots (hm ²)	Cutting intensity
Plots of control method	262	205.2	1987-1988	0.04-0.09	8%-20%
Plots of fast-growing and high -yield	20	3.655	1986	0.135-0.21	2%-60%
Fixed plots	4	2	1986	0.5	0
Other plots	3	0.818	1986-1987	0.2-0.3	6%-15%

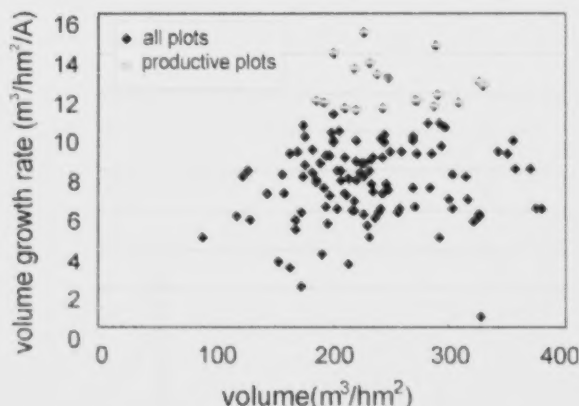


Figure 1. The volume growth rate of all plots and productive plots.

The optimum stand structure is defined as follow: volume is 185-330 m^3/hm^2 ; volume growth rate is 11-15 $\text{m}^3/(\text{hm}^2 \cdot \text{A})$; scale of conifer verse broadleaf is 6:4 to 8:2; the number of trees is 800-1400 per hectare; proportion of trees with small, middle and large diameter is 25.8%-55.0%, 28.3%-48.7% and 5%-31.5%; the parameters of negative exponential distribution is a (-0.1358, -0.0854), K (125.660, 712.820); q is between 1.268-1.580; the selected cutting density is 10%-20%; cutting cycle is 10-20 years. Because forest has different stages of development, this optimum stand structure is temporary.

Discussion

It is suggested that the diameter structure curve of uneven mixed forest displayed with two peaks normally and irregular while the forest forms in

disorder (T.W. Daniel 1979). It is considered to be effective to improve stand structure with a cutting density of 20%-30% (Zachara 2000). The suggested management objective is: 300 m^3/hm^2 of average volume, 7-8 m^3/hm^2 of volume growth rate, and 7:3 of conifer verse broadleaf (Mingfang Yin et al. 2005). But these findings are not fit for the over-cutting forest very well.

In our point, we should go on with monitoring stand dynamics of forests, and we shall take factors of climate and ecology into consideration.

Conclusion

The optimum stand structure we put forward should be taken as the management objective of over-cutting forest on North Slope of Changbai Mountain. We will further the study with considering factors of climate and ecology.

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Impacts of Forest Ecosystem Management in the Boreal Forest: Example of the Lake Duparquet Research and Teaching Forest

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Introduction

Mitigating the cumulative effects of harvesting on boreal forest landscapes has become a political issue in much of Canada. Natural disturbance-based management, a variant of forest ecosystem management, proposes setting targets for the maintenance of historical forest cover using a cohort-based model or framework (Bergeron et al. 1999). This model is based on a theoretical forest landscape composition as a function of regional fire regime and natural stand dynamics. The multi-cohort framework reflects three broad stand development phases. First cohort (post-fire) stands are generally dense and composed of shade intolerant species; second cohort stands tend to be a mix of shade intolerant and tolerant species; and third cohort stands are generally more open and mainly composed of shade tolerant species (Figure 1). Stand structure tends to move from simple even-aged to more complex structures as stands develop through cohorts 1 to 3. Although natural disturbance-based management acknowledges the importance of considering complex stand-level dynamics, landscape-level forest planning often tends to oversimplify this aspect.

The first objective of this study was to measure the historical landscape structure according to the cohort model and to interpret these measures in terms of forest-level management objectives for maintaining the natural forest mosaic. The second objective was to identify impacts of different cutblock-dispersion scenarios on landscape structure and on wood procurement costs.

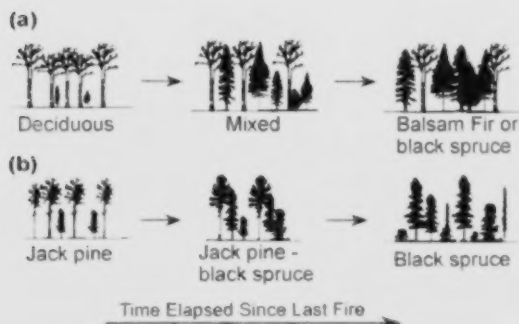


Figure 1. Simplified stand succession pathways for the mixed fir-birch forest type on a) mesic sites and b) dry sites (Lesieur et al. 2002)

Materials and Methods

Temporal variation in landscape structure was measured using a limited number of landscape spatial indices (LSI) (McGarigal and Marks 1994) that could be easily translated into management objectives. These include: proportion of the landscape occupied by the different cohorts; mean stand size, mean distance to nearest neighbour, and a shape index normalized by area weighted mean patch fractal dimension. These indices were calculated for four forest cover maps of the Lake Duparquet Research and Teaching Forest (LDRTF) dating from 1965, 1972, 1983 and 1994 in which each stand polygon was associated with one of three cohorts. We used observed minimum and maximum values of the four indices for establishing spatial configuration objectives that could be used by managers for maintaining historical forest structure.

A hierarchical approach to scenario simulation was used in which simulations were done at the stand level but impacts evaluated at the landscape level. We used FOREXPERT-UQAT, a functional stand-level model, to simulate three management scenarios and to evaluate their impact on forest age structure and configuration at the landscape level: 1) a dispersed-cutting scenario that reflected provincial forest intervention regulations (RNI); 2) a natural disturbance-based scenario that followed current management guidelines in the LDRTF (Eco1); and 3) a modified natural disturbance-based scenario with the added constraint of maintaining historical proportions of the different forest cover types identified in the first part of the study (Eco+). Impacts on landscape structure were measured as a function of divergence from historical limits. Finally, a spatial harvest simulation tool (WPPT) was used to estimate the consequences for direct wood procurement costs of the three management scenarios.

Results

Results of the historical analysis of landscape structure are shown in Table 1. The forest matrix is dominated by third cohort stands; other stand types are variably dispersed within this generally old-forest landscape. First cohort stands are quite large with irregular shapes. Second cohort stands are smaller, dispersed and had more regular shapes.

Simulation of the three management scenarios revealed the degree to which each of the three approaches adhered to or diverged from historical values of landscape indicators (Table 2). The RNI and Eco1 scenarios, in particular, produced considerable divergence from historical spatial characteristics of the forest, notably with respect to the over-occupation of first cohort stands (a direct result of even-aged management). Although the modified ecosystem management scenario, Eco+, respects landscape occupation objectives for the three cohorts, it still falls short on stand size objectives for the first and second cohorts and dispersion objectives for first cohort stands.

The cut block dispersion rules applied in the RNI scenario resulted in higher wood procurement costs early in the simulation horizon compared to the Eco1 scenario (Figure 2). These differences are a result of costs related to road construction and maintenance. In effect, the RNI scenario required more rapid development of a road network that was also more extensive, especially in the first 50 years of the planning horizon.

Discussion

Current forest regulations (RNI) and the original LDRTF management plan (Eco1) both appear to generate landscapes that diverge from the historical structure and configuration. There are a number of reasons for this outcome. First, the landscape-level objectives of the management plan are based on fire history studies of a 15,000 km² area in which the research forest is located. However, the LDRTF is quite small (80 km²) relative to the area generally affected by major stand-replacing fires in the region, and consequently is not at equilibrium with the regional fire regime.

Table 1. General management objectives derived from the historical landscape analysis.

	Landscape occupation	Stand size	Dispersion	Stand shape
Cohort 1	Frequent	Intermediate	Intermediate	Complex
Cohort 2	Rare	Small	Dispersed	Simple
Cohort 3	Dominant	Extensive	Aggregated	Intermediate

Table 2. Summary of adherence/divergence of landscape objectives at the end (100 years) for three management scenarios.

Cohorts	Scenarios								
	RNI*			Eco1*			Eco+*		
Landscape occupation	+	-	-	+	-	-	0	0	0
Stand size	0	-	0	0	0	0	-	+	0
Dispersion	-	+	0	-	+	+	-	0	0
Stand shape	0	0	0	0	0	0	0	0	0

* Symbols -, + and 0 indicate results are below, above or within management objectives, based on historical limits.

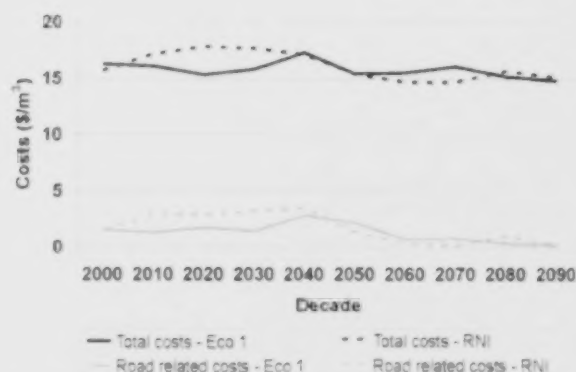


Figure 2. Evolution of the road network according to time for the two main scenarios.

The relatively small area of the research forest and the difference between its current condition and the regional fire cycle reference are in part responsible for divergences in landscape management objectives and outcomes of simulations. Second, because the method used in LDRTF is area-based and non-spatial, it lacks sensitivity related to stand accessibility and volume constraints. Finally, canopy replacement and secondary disturbances are not well treated by FOREXPRT-UQAT. The simplification of stand dynamics probably results in lower transition levels from first to second and third cohort stands.

Conclusion

This study uses the concept of cohorts to scale up from the stand- to landscape-level to (1) identify historical variability of several indices of forest landscape structure; (2) establish management objectives for the LDRTF and (3) evaluate the outcomes of three management scenarios on these indices and on wood procurement costs. Imposing landscape-level objectives based on historical values has the effect of adding constraints to forest management. For the development of a future management plan, we suggest the use of a spatially explicit, volume/area based tools that permit optimization of management scenarios under conflicting objectives such as conservation of landscape structure, forest age regulation, and maximum yield. Trade-offs between higher costs associated with a more complex road system and higher AAC expected from improved stand accessibility need to be evaluated.

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**Dynamics of
Complex Stand
Structures**

Integrating Dynamics Into Management of Complex Forests: Seeking Balance in an Unbalanced World

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An international trend in forest management is towards increasing the complexity of forest stands. This complexity is generally realized in the form of greater complexity in stand structure through greater species diversity and more than one age class of trees. Since forest management has emphasized simpler stand structures for several decades, managers often find themselves struggling for guidance on what structures these stands should obtain. Unfortunately, guidance is scarce and what guidance is available is often based on anecdotal information or out-dated ecological concepts.

Conceptual models that are used to provide guidance for the management of complex structures include simple percentages of species in a stand, diameter distributions, age structures, and frequencies of disturbances. Much of the impetus for these "models" comes from ecological concepts about balanced ecosystems, equilibriums in ecosystem structure or function, "stability" of ecosystems, resiliencies and resistances to disturbances. Managers then attempt to design stand structures that are balanced, in equilibrium, stable, and resilient, or resistant to perturbations. The general effect is to simplify stand structures and homogenize landscapes.

When we examine the dynamics of complex stands we find that species composition can shift during even-aged stand development as some species advance through their life cycles quickly and die, others die from self-thinning, and some species achieve dominance at different times. These patterns have been observed in many mixed-species, even-aged stands: multiaged stands are likely more complex. Multiaged stands are commonly managed to conform to particular diameter distributions. In North America and many other places, a simple negative exponential distribution is the most common form of this distribution. However, this distribution is arbitrary and

when applied over large areas results in landscape-level homogenization of stand structure. Age structures in multiaged stands are often assumed to be all-aged thereby implying the need for continuous regeneration.

Disturbances are one of the most important dynamics in the creation of complex stand structures. The concepts of stability, resistance and resilience generally refer to immediate and longer-term responses to disturbances. Stands that are stable, resistant and resilient are desirable and managers strive to design stands with these characteristics. However, guidance is generally lacking and those few models that do exist tend to push stands towards a small number of stand structures. Additionally, when disturbance intervals are used to guide treatments they tend to encourage regular treatment intervals which also often assumed to be constant over time thereby requiring treatments on regular intervals.

The challenges – as we attempt to predict the outcomes of managing for complex structures or the effects of natural processes – are to avoid the pitfalls of oversimplifying our models and our management thereby countering the objectives of these forest management trends or limiting the potential of our models to predict the outcome of these complex phenomena. We are being pulled by two forces: one is the combination of human nature to assume our environment is somehow balanced and our need as researchers to simplify assumptions to develop our models and guidelines for management. At the same time, the complexity that is required in today's forestry necessitates that we enhance complexity and avoid simplifying assumptions. Our task is then to be cognizant of these forces and cautious as we move forward.

Effect of Stand Structure on Stone Pine (*Pinus pinea* L.) Regeneration Dynamics

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Introduction

Natural regeneration of disturbed Mediterranean forest ecosystems is very slow and fraught with problems. Several reasons for the lack of success in Mediterranean forest ecosystems included: (i) the characteristics of the Mediterranean-type ecosystems climate; (ii) the masting habits of most Mediterranean species; (iii) the low density of Mediterranean stands; and (iv) the impact of grazing on seedlings. Stone pine shows two further limitations: (i) the large size of its seed (a pinyon), which reduces seed dispersal; and (ii) the commercial use of the pinyon, that leads land owners to modify the regeneration method and restrict the natural regeneration in order to achieve good pinyon yields.

Under this scenario, natural regeneration has resulted in a continuous failure in stone pine stands. Forest managers should now adopt measures to ameliorate the regeneration process, which is a key factor in determining the future forest structure. A first step is to identify the spatial pattern of adult trees and seedlings. When stems are mapped, one of the most widely used methods in plant ecology to characterise the spatial pattern is Ripley's K (Ripley 1977). In addition, the intertype $L_{rs}(d)$ function (Lotwick and Silvermann 1982) describes the spatial relationship between plants belonging to two different classes. To test how regeneration varies with the proximity to the crowns, the point pattern analysis is extended to deal with objects of finite size and irregular shape (Wiegand et al 2006). We hypothesize that this approach could give us more insight in the smaller scales relationships than the traditional point pattern, allowing us to consider a third dimension in which offspring grows under the crowns. The objectives of our study were 1) to identify the spatial pattern of recruitment; 2) to evaluate the influence of overstory on the spatial pattern of seedlings and saplings, by the extension of point pattern analysis to finite size objects; 3) to model the spatial patterns of seedling and sapling recruitment.

Methods

The present study investigates the effect of the silvicultural system and reproductive method applied

and the resulting stand structure on the spatial pattern of Stone pine regeneration in two different types of stand structures: an even-aged stand and an uneven multi-aged stand. Data were collected on two 4800 m² plots located on the Spanish Northern Plateau, sited in continental sandy soils. No treatments have been applied in the plots since 1987. Within the plots, every pine more than 20 cm high was located through its coordinates XY. For trees with breast height diameter larger than 5 cm, total height, crown diameter and total age were measured. In seedlings, only total height and crown diameter were measured.

To identify the dynamics of the univariate spatial pattern of trees and regeneration the L transformed version of Ripley's K univariate and bivariate functions was used. The patterns for regeneration were not homogeneous, thus, a heterogeneous Poisson process null model was used as an alternative to complete spatial randomness (CSR). In this null model the constant intensity of the homogeneous Poisson process is replaced by an intensity function $\lambda(x,y)$ that varies with location, but the occurrence of any point is kept independent from any other point. The spatial relationship between regeneration, adult trees and stumps was analysed with the intertype $L_{rs}(d)$ function (Lotwick and Silvermann 1982). Null model of antecedent conditions, in which we maintained the position of the parent trees and randomized the location of the offspring following a Neyman-Scott process (1958), was used to test competition or facilitation by the crowns. The toroidal rotation model was used to test the null hypothesis of the independence between the two patterns. We used the finite size analysis approach (Wiegand et al. 2006) to detect the small-scale interactions between the crowns of the trees and regeneration.

Aggregated patterns of regeneration are modelled in both stands. We used a Poisson cluster process (Diggle 1983). Parents or cluster centres can be generated by a CSR process with an intensity of ρ or they can be kept from the actual parent tree pattern. These parents generate offsprings that are independently located relative to their parents following a bivariate normal distribution relative to the parent trees with mean 0 and variance σ^2 . The

unknown parameters ρ and σ were fitted comparing the theoretical and the empirical $K(t)$ functions (Diggle 1983).

$$K = \pi \cdot t^2 + \frac{1 - e^{(-t^2/4\sigma^2)}}{\rho}$$

Results

The initial trees showed overdispersion at small scales and appear to be randomly distributed for the rest of scales examined. Regeneration was highly aggregated for seedlings and saplings, in both the even and the uneven multi-aged Stone pine stands. The intensity of the pattern in the even-aged stand increased for saplings, while the peak moved from 5 to 15 m in seedlings to a distance of 5-6 m for saplings. In the even-aged stand, both seedlings and saplings showed a clumped distribution at all the scales examined. Seedlings showed a peak at 9 m, while saplings showed a patchy distribution at two different scales, at 5 m and at 16 m.

When studied with the finite size approach, regeneration exhibited a negative correlation with the initial trees in the first meters in both stands. This negative correlation is not detected with the point pattern approach. In the uneven-aged stand there is a positive association for the first metres that is depicted by the point pattern approach, which showed no association. When we examined the relationship between saplings and parent trees in the uneven-aged stand, the finite size approach also revealed a negative association in the first metres and a positive correlation for the following meters, that was not detected by the point pattern analysis, which showed negative association for all the scales studied. In both Stone pine stands, a positive spatial association existed between seedlings and saplings indicating that they occupy the same microsites. A positive spatial association was also found between regeneration higher than 20 cm and stumps greater than 20 cm in diameter, left as witnesses of the last cutting 15 years ago in the uneven multi-aged *Pinus pinea* stand.

The Poisson clustered process was an adequate model for simulating the initial and ingrowth patterns. The initial trees were used as common centres for both dispersions to reflect the dependence in the patterns. The empirical functions for the four models are inside the 95% confidence envelopes at the scales studied.

Discussion and Conclusions

Seed dispersal by gravity in Stone pine trees creates a small scale clustering of recruits due to the effect of parent proximity. The spatial dependence between the ingrowth and the position of the existing trees found suggests that regeneration is unlikely outside the crowns of the trees in Stone pine stands, as has been previously suggested (Calama and Montero 2007). Survival is favoured by the shade and microclimatic conditions provided by close proximity to overstory trees, as observed in other dry environments (Fajardo et al. 2006). Positive correlation between seedlings and saplings observed under both type of managed stands may be caused by local differences in soil or water availability that create favourable seedbed for germination and growth. Considering the crowns instead of points in the pattern analyses reveals us more detailed information of the relationships at small scales. The aggregated spatial patterns of ingrowth trees found in these stands, are usually observed in the recruitment of pine species, and can be modelled effectively by the use of Poisson cluster processes as has been previously done with other pine species (Camarero et al. 2005).

The study underlines the importance of crowns and favourable microsites in Stone pine regeneration. Keeping higher densities of parent trees will improve the amount of seed and could create favourable conditions for offspring development. A detailed description of the spatial patterns provides managers with information to enhance the regeneration in Stone pine forests.

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Dynamics of Live Tree Structural Diversity of the Boreal Forest in Central Canada

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Introduction

Stand structural diversity of live trees is critical to bird species diversity⁹ and habitat suitability for other animals^{11,13}. In the Canadian boreal forest, the stand structure of live trees is theorized to change from relatively homogeneous in the diameter and height to bimodal and then multimodal with a broad range of heights and diameters during stand development^{1,3,7}, suggesting increasing structural diversity with stand ageing. However, little empirical data supports this theoretical generalization of structural dynamics.

Many stand characteristics differ with stand composition including coarse woody debris types and amounts¹, productivity^{2,8}, and understory plant diversity^{4,5}. Mixed-species stands may be more structurally diverse than single-species stands because of inherent differences in growth rates and successional niches of component species in mixtures^{6,10}. However, although conifer, broadleaf, and mixedwood types all commonly occur in the North American boreal mixedwood forest, no studies have tested if mixedwoods are more structurally diverse than conifer or broadleaf stand types. We hypothesize that mixedwoods are more structurally diverse than conifer and broadleaf stand types because of the different growth rates and regeneration mechanisms of component species in mixedwoods.

In contrast to some studies where a chronosequence is selected with or without canopy succession, this study attempted to examine independent and interacting effects of overstory type and time since stand-replacing fire (TSF) on stand structure. Specifically, our hypotheses were: (1) stand structural diversity increases with TSF and (2) mixed-species stands have higher stand structural diversity compared to single-species stands. To facilitate testing these hypotheses, we quantified stand structure using two commonly used indices: Shannon's index (H') and coefficient of variation (CV)^{9,14,15}. While both indices reach minima when all trees fall within a single size class, H' reaches a maximum when trees range widely in diameters or heights and are evenly distributed. However, CV reaches a maximum with a two-storied stand containing trees with a large difference in diameters and heights between the two stories.

Materials and Methods

The study was conducted in the boreal forest north of Lake Superior and west of Lake Nipigon approximately 150 km north of Thunder Bay, Ontario. We studied three overstory composition types: (1) conifer; dominated by jack pine in early stages of development and a mixture of black spruce, white spruce, and balsam fir later in stand development, (2) broadleaf; dominated by trembling aspen at early stages of development and paper birch later in stand development, and (3) mixedwood; dominated by a mixture of jack pine and trembling aspen in early stages of development and a mixture of black spruce, white spruce, balsam fir, and paper birch later in stand development. Stand type was assessed based on the basal area of conifer trees in the stand. Stands with greater than 70% conifer basal area were classified as 'conifer type'; stands with 30 to 70% conifer basal area were classified as 'mixedwood type'; and stands with less than 30% conifer basal area were classified as 'broadleaf type'. In each stand type, TSF varied from 72 or 80 to 201 years. A total of 36 fire-origin stands were sampled with twelve stands for each overstory composition type.

Within each stand, a 400 m² circular plot was established to represent the stand. Within the plot, the diameter at breast-height (DBH) of all trees (DBH ≥ 10 cm) were measured. We randomly selected five trees from each 5-cm DBH class for each species, and their heights were measured. Tree heights for the remaining trees were estimated using species-specific non-linear regression models developed from the paired height and DBH measurements using the Chapman-Richards function. Quantification of tree-size variability as an indication of stand structural diversity was performed using H' . To determine if stand structural diversity, volume, and density differ with TSF and stand type, multiple regression analyses were conducted.

Results

DBH-based H' differed significantly with TSF and stand type, while height-based H' differed marginally with TSF and stand type. DBH-based H' followed an inverse U-shaped pattern with TSF for all stand types

with the highest diversity occurring in 124- to 139-year-old stands. Among stand types, mixedwoods had greater DBH-based H' in older stands than the other types, while broadleaf stands had the lowest DBH-based H' in the 72- to 90-year-old stands. Height-based H' decreased marginally from 124-139 to 201-year-old stands in all stand types, while broadleaf had the greatest height-based H' in 124 to 139-year-old stands. Mixedwoods had the highest height-based H' in 72- to 90-year-old stands, while conifer stands were the least diverse stand type in 124-139 and 201-year-old stands.

DBH-based CV also differed significantly with TSF and stand type, while height-based CV only differed significantly with TSF with a marginally significant stand-type effect. Regardless of stand type, both indices indicated that CV was highest in 124- to 139-year-old stands. Among stand types, mixedwoods had the highest DBH-based CV in the 72- to 90- and 201-year-old age classes and were equally diverse to conifer and broadleaf types in the 124- to 139-year-old age class. Similarly, mixedwoods had the highest height-based CV in the 72- to 90-year-old age class and were equally diverse to broadleaf stands in the 124-139 and 201-year-old age classes, while conifer stands had the lowest tree height variability in the 201-year-old age class.

Discussion

All four diversity indices indicated that stand structural diversity varied significantly or marginally significantly with TSF and stand type from 72 to 201 years. Our hypothesis that structural diversity measured using H' increases with TSF was partially supported. Structural diversity measured using DBH-based H' increased from 72 to 124-139 years since fire, but declined in 201-year-old stands for all stand types. Height-based H' showed a similar pattern in broadleaf stands, but it decreased as TSF increased in conifer and mixedwood stands.

Our hypothesis that stand structural diversity, measured using CV, should be inversely U-shaped with TSF is supported by our findings. The highest CV occurred in the 124 to 139-year-old age class, which corresponds to the stand reaching over-maturity and undergoing extensive canopy breakup, with several tall, large-diameter pioneering trees that are near the limit of their life expectancy and many smaller-diameter late successional trees that established at various times throughout succession, creating a largely bimodal stand structure. Paré & Bergeron¹² reported similar structural trends as our study, finding

that the vertical distribution of cumulative crown width develops from a single layer at the age of 27 years, to bimodal at the age between 47 to 121 years, to multimodal at the age of 144 to 168 years, and to a continuous layer at an age of 231 years.

Mixedwoods were found to be more than or equally as structurally diverse as single-species stands. Species that have different life traits growing in mixtures can undergo extensive vertical canopy stratification and create a diverse structured tree layer, in contrast to species with similar life traits, which compete for the same growing space. Our findings are similar to those of Varga et al.¹⁶, who reported that tree-canopy differentiation increased as percent lodgepole pine decreased in lodgepole pine-black spruce forests, but no significant mixed-species effect occurred when percent western hemlock varied in western hemlock-western redcedar forests in British Columbia, Canada.

Conclusions

Our data only partially supported our first hypothesis that the structural diversity of live trees increases with stand development from the canopy transition to gap dynamics stage. The 124 to 139-year-old stands appeared to be the most diverse, based on the metrics we measured. Our second hypothesis that mixed-species stands are more diverse than single-species stands was also only partially supported, as mixedwoods were more than or equally as diverse as conifer and broadleaf types, depending on the stand development stage and diversity index used.

Acknowledgements

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Dynamics of Commercial Tree Species After Logging in Tropical Rainforest

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Introduction

For most tropical moist forests, polycyclic forest management systems are perceived to be ecologically more appropriate than monocyclic systems (Bawa and Seidler 1998, Montagnini and Jordan 2005). This system is based on the premise that following harvest, sufficient growing stock is retained and natural regeneration of commercial species is achieved to provide enough harvestable wood for consecutive logging cycles. The exploitation norms including the minimum harvestable diameter (MHD) and the cutting cycle (CC) length have to be fixed accordingly (Eba'a 2000, Borie 2000). To determine these parameters, the present forest stand structure and species composition as well as the spatial and temporal dynamics of commercial tree species populations and their growth after harvesting must be known.

This research aims at assessing the post-logging changes in natural regeneration and growing stock of commercial species in tropical forests in south-eastern Cameroon. Since the extraction rate in these forests is very low (1 tree per 2 ha), we focused the investigations of stand structural changes around the gaps created through harvesting. The specific objectives was to assess the influence of harvesting gaps on the density and species richness of commercial tree regeneration and growing stock at different times following selective logging in different stand locations associated with gaps. Information about stand dynamics underpinning sustainable forest management is urgently needed in Southeast Cameroon (Eba'a 2000, Hall et al. 2003), where forest exploitation has been conducted for several decades despite the lack of reliable information on post-logging stand development (FAO 2003, Hall et al. 2003).

Materials and Methods

This investigation took place in Southeast Cameroon between January 2004 and Mai 2006. This part of the lowland tropical rainforest is located between 13°60'–13°80'E and 3°70'–3°90' N at about 650 m a.s.l. The

forests in this region are rich in commercial tree species (37), however, only a fraction of these are actually harvested. The annual rainfall of 1 600 mm is evenly distributed throughout the rainy season. The vegetation is classified as tropical semi deciduous primary rainforest (Hall et al. 2003). Soil types are broadly classified as Oxisols (Hall et al. 2003).

To investigate the temporal dynamics following logging, four selectively logged forest concessions of 0, 6, 12, and 25 years since harvesting were identified on maps. Within each selected concession, 30 to 40 gaps were randomly chosen. At each gap, a 20 m X 100 m transect was laid along the disturbance gradient ranging from the highly disturbed side of the gap where the tree fell, to the side opposite the felling direction showing the least disturbance. In order to investigate the effect of stand position associated with gaps, five 20 m X 20 m adjacent subplots were demarcated within each transect (Figure 1).

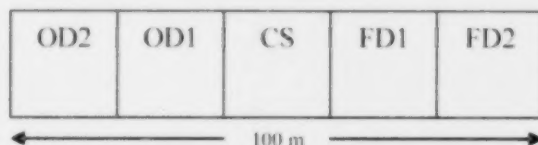


Figure 1. Positions of the 5 subplots within the 20 m X 100 m transects associated with gaps. CS=central subplot called (CS) was demarcated around the stump of the removed tree, FD1 and FD2 were demarcated in the felling direction of the tree, and OD1, OD2 were least disturbed plots in the opposite direction of the felling.

Thirty other identical subplots were demarcated and inventoried in unlogged primary forest and considered as control. All the individuals of the timber species down to the early sapling stages (taller than 1 m) were identified and recorded. Larger individuals with diameter at breast height (DBH) ≥ 10 cm were recorded separately from smaller trees with DBH < 10 cm.

To investigate the effects of time since harvesting and gap position on regeneration and tree density and stand basal we used ANOVA and regression approaches. All statistical analysis was done using the JMP IN® version of the SAS software. (Sall et al. 2001).

Results

Both gap age ($P < 0.0001$) and subplot position around gaps ($P = 0.002$) significantly influenced regeneration density. Regeneration density increased with time in all subplot locations (Figure 2). Here only the trends of the gap centre and the subplots in felling and opposite direction furthest away from the gap centre are depicted, since the subplots in the same directions but closer to the gap centre did not show significantly different results from those further away.

Around young gaps, there was no significant difference in regeneration density between the subplots: CS, FD1 and FD2. Six years after logging the regeneration density had already increased up to the initial value in all subplots along the disturbance gradient. Regeneration density increased fastest in the subplots with most canopy disturbance (CS) when compared to the other subplots around the gaps. After 25 years the regeneration density in all subplots had reached or exceeded the level found in undisturbed forest. However, this recovery is only in terms of total stem numbers irrespective of the harvested species. In

fact some of the harvested species like *Triplachiton scleroxylon* hardly regenerated after logging.

Tree density and stand basal area were also affected by gap age ($P < 0.0001$) and subplot position ($P < 0.001$) within the transect (Figure 3). Except in the furthest subplot (OD2) from the gap centre in the opposite direction of the felling, both basal area and stem numbers increased significantly with time. Here only basal area in the gap centre and the subplots in felling and opposite directions furthest away from the gap centre are depicted.

There appeared to be no increase in tree density and stand basal area during the first 12 years after logging. In spite of the slow recovery during the first 12 years following harvesting, the total commercial tree density and basal area in and around 25 year old gaps had reached the level found in undisturbed forest. Significant differences in tree density and stand basal area were found only between the felling and opposite directions but no significant difference was found between subplots in the same direction from the gap centre. The most common commercial trees species represented by at least 30 individuals, were: *Desbordesia glaucescens*, *Guarea cedrata*, *G. thompsonii*, *Piptadenistrum africanum*, *Eriobroma oblongum*, *Alstonia boonei*, *Klainedoxa gabonensis*, *Terminalia superba*, *Pycnanthus angolensis*, *Milicia*

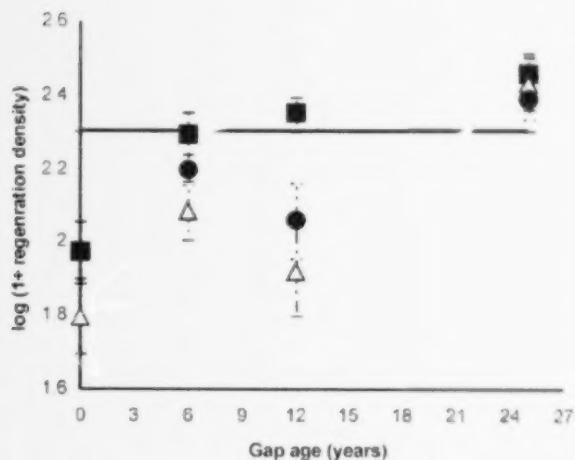


Figure 2. The increase in regeneration density of commercial species in the stand positions associated with gaps at different times after wood harvesting. Horizontal line represents the control level in undisturbed forests. (■)= central gap plot, (△)=FD2-furthest subplot from centre in felling direction, and (●)=OD2-furthest subplot from centre in the opposite direction. Each point represents the average of 17 to 41 replicate gap plots.

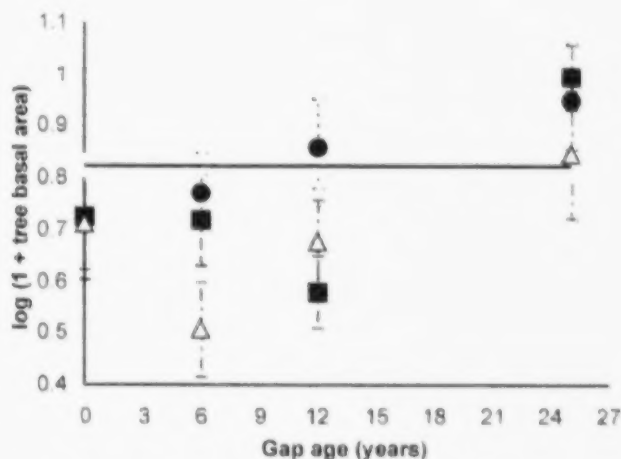


Figure 3. The increase in basal area of commercial species in the stand positions associated with gaps at different times after wood harvesting. Horizontal line represents the control level in undisturbed forests. (■)= central gap plot, (△)=FD2-furthest subplot from centre in felling direction, and (●)=OD2-furthest subplot from centre in the opposite direction. Each point represents the average of 17 to 41 replicate gap plots.

excelsa, *Entandrophragma candollei*, *Gambeya africana*, *Staudtia kamerunensis*, *Cylicodiscus gabunensis*, *Fagara heitzii*, *Pteleopsis hylodendron*, and *Antrocaryon micraster*.

Discussion

Although the forest stands around the gaps seem to have recovered in term of stem density and basal area 25 years after logging, the commercial species richness of the new stand is different. Large trees of highly valuable tree species have been replaced by small trees of species with lower commercial value, as has also been found by Hall et al. (2003). Some commercial timber species did not regenerate well under the environmental conditions in logging gaps. The conditions in and around the gaps favor the development of some highly light demanding species like *Fagara heitzii*, *Canarium schweinfurthii*, and disadvantage other species like *Petersianthus macrocarpus*, *Lovoa trichilioides*. For this reason, the forest around the gaps has not really recovered from logging disturbance. However, for an evaluation of the selective system used here, the growth rate and regeneration of commercial species in the forest matrix which is uninfluenced by gaps also needs to be considered. The gap age and plot position along the disturbance gradient could explain only 40 % of the variation in regeneration density, 36 % of the variation in tree density and 30 % of the variation in stand basal area. For a better understanding of the tropical forest dynamics after logging, further investigations should be carried out to assess the effect of other relevant environmental factors like soil properties, competition of non commercial tree specie like: umbrella trees (*Musanga cecropioides*) which is by far, the most dominant and abundant tree species in and around the logging gaps.

Conclusion

This investigation revealed persistent differences between the exploited and the unlogged stands in terms of structure, commercial species richness, big stem density and basal area of some commercial tree species 25 years after logging. Without information about the stem growth of trees of commercial species in the remaining stand area, we can not assess whether timber production is sustainable. This information is currently collected through tree ring analysis. However, some valuable commercial species are either absent (*Triplochiton scleroxylon*) or rare, suggesting that, gaps were either of insufficient size or there were limitations to seed dispersal.

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Height and Diameter Growth Following Thinning in Uneven-Aged Douglas-fir Stands

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Introduction

This paper addresses 11-year diameter at breast height (dbh) and height growth following precommercial thinning from below in uneven-aged Douglas-fir (*Pseudotsuga menziesii* var. *glauca*) stands in central British Columbia, Canada. Our specific interest is in how assessment of individual tree response to the release provided by the thinning is impacted by the criteria used to select the trees considered for response.

The thinning experiment was established in stands which were diameter-limited logged in the 1960s, at which time many of the trees greater than 10 inches (24 cm) dbh were removed. By the late 1980s, residual stands were dominated by dense patches of trees less than 15 cm dbh, with a relatively sparse overstory of larger dbh trees. Douglas-fir was by far the most prevalent species, accounting for approximately 90% of the trees. Other tree species present were lodgepole pine (*Pinus contorta* var. *latifolia*), spruce (*Picea glauca*, *Picea engelmanni* and their crosses), white birch (*Betula papyrifera*) and trembling aspen (*Populus tremuloides*).

Three blocks (replicates), of 40 ha each, were established and divided into approximately equal quadrates. One of three thinning treatments and a control (C) were randomly assigned to each quadrate. The thinning treatments consisted of two "clumped" treatments where small trees were left at closer intervals within clumps and clumps were spaced at least 3 m (C1) or 5 m (C2) apart. The third thinning treatment (S) was the standard at the time, where smaller trees were spaced at 2.5 m apart throughout the stand. Two 0.05 ha plots were subjectively located in dense patches within each quadrate prior to thinning, for a total of 24 plots (3 blocks $\times$ 4 treatments $\times$ 2 plots). Pre-treatment conditions were assessed on each of the plots in 1989 and the thinning treatments were applied in the winter of 1989-1990 (Marshall 1996). Measurements of the residual trees on these plots were made following the 1992, 1996, and 2003 growing seasons. In this paper we focus on single tree height and dbh growth between 1992 and 2003 (11 years).

The GLM procedure in SAS was used to fit single tree dbh growth and height growth as a function of tree dbh in 1993, treatment, block, and block $\times$ treatment; Duncan's multiple range test was used to compare treatment means. Increasingly restrictive subsets of trees were used in fitting this model. The least restrictive dataset consisted of all undamaged trees. The model was then refit using only the conifer species, and finally only with Douglas-fir. We then considered only the trees growing in the most prevalent size classes (between 2.5 cm and 17.5 cm). We divided this range into three 5-cm dbh classes and selected the "best X" Douglas-fir trees in each class in each plot, with "best" defined as those trees growing the fastest. We considered subsets of up to 75, 50, 30, 25, 20, and 15 trees in each dbh class. If a dbh class contained less than X trees, then all the trees in that class were used.



Figure 1. Study site location.

Table 1. Differences in mean tree dbh and height growth among treatments by data set.

Data Set	N	11-Year DBH Growth (cm)				11-Year Height Growth (m)			
		C2 ^a	C1 ^b	S ^c	C ^d	C2	C1	S	C
All	3042	2.60 a ^f	1.84 c	2.08 b	0.84 d	2.20 a	2.20 a	2.04 b	1.39 c
All Conifer	2966	2.64 a	1.87 c	2.10 b	0.84 d	2.20 a	2.20 a	2.05 b	1.37 c
Only Fd	2636	2.57 a	1.92 c	2.12 b	0.82 d	2.08 a	2.17 a	2.07 a	1.35 c
Best ^g 75	1906	2.56 a	1.90 c	2.03 b	1.10 d	2.16 ab	2.25 a	2.09 b	1.80 c
Best 50	1683	2.56 a	1.90 c	2.04 b	1.28 d	2.16 ab	2.25 a	2.10 b	2.04 b
Best 30	1433	2.63 a	1.89 c	2.12 b	1.45 d	2.22 a	2.28 a	2.17 a	2.26 a
Best 25	1307	2.69 a	1.96 c	2.18 b	1.50 d	2.28 a	2.35 a	2.22 a	2.34 a
Best 20	1187	2.80 a	2.03 c	2.24 b	1.57 d	2.37 ab	2.43 a	2.27 b	2.44 a
Best 15	901	2.90 a	2.21 b	2.31 b	1.67 c	2.51 ab	2.63 a	2.40 b	2.59 a

Results

All components of the model were highly significant ($p < 0.0001$) for dbh growth, regardless of the dataset employed. The best dbh growth occurred in C2, followed by S, C1, and lastly the control (C) (Table 1). The difference between the best growth rate and the worst ranged from 1.80 cm using the All Conifer dataset to 1.18 cm using the Best 30 dataset.

Although all components of the model were significant at $\alpha = 0.05$ for height growth regardless of the dataset employed, the assessment of what the differences were among treatments was sensitive to the dataset used (Table 1). With the larger datasets, individual tree height growth on the thinned plots exceeded those on the control plots. However, for the Best 50 dataset, average height growth on the control plots was very nearly that of the thinned plots, and for the Best 30 and more restrictive datasets the average height growth on the control plots exceeded that of at least one of the thinned plots.

Discussion

Many of the small trees in these stands were growing poorly prior to the thinning. Removal of many of those trees by thinning and leaving the better growing trees can create the appearance that residual trees on thinned stands are growing faster on average after thinning than trees in control areas, even if there is no real growth response. This has been called by some "the chain saw effect".

The apparent impact of the "chain saw effect" was much larger when assessing height growth than it when assessing dbh growth. The average height growth for trees on the control plot increased by 1.20 m from the largest dataset to the smallest; this represents almost a

100% increase. The corresponding increase in average height growth for the thinned plots varied from 0.31 (C2) to 0.43 (C1), an increase of only about 20%. This is probably not surprising given the understory nature of many of the small dbh trees. On the control plots, a significant number of these trees lacked distinctive leaders and consequently were growing very slowly in height. However, growing conditions were patchy, and some small dbh trees on the control plots were growing well. When the thinning treatments were applied, operators were instructed to leave "better looking" trees as residuals, everything else being equal. Focusing only on the better growing trees in the control plots removed the height growth response to thinning which might have been concluded if only the larger data sets were used.

Conclusion

The choice of dataset had no impact on the ordering of the treatments for single tree dbh growth following thinning. However, height growth differences among treatments were considerably more sensitive to the dataset. The average height growth of trees on the control plots was significantly lower than those on the thinned plots when assessed using the larger datasets with fewer composition restrictions. With more restrictions placed on the datasets, the average height growth on the control plots was similar to that of the thinned plots.

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Modelling the Species Composition Dynamics of Aspen in Boreal Mixedwoods

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Introduction

Boreal mixedwoods are some of the most productive and diverse forest ecosystems in Canada, with the stands typically consisting of mixtures of aspen (*Populus tremuloides*) and white spruce (*Picea glauca*), along with other species such as balsam poplar, balsam fir, black spruce, white birch and jack pine. Although it is known that the proportion of aspen in the mixtures has a profound impact on the growth of white spruce and on the total volume of the mixedwoods (Man and Lieffers 1999), very limited work has been done to quantify and model this proportion. In this study, the aspen proportion in mixedwoods was expressed by its species composition (SC), defined as the ratio of aspen basal area (BA_{aspen} , m²/ha) to total stand basal area (BA_{total} , m²/ha):

$$[1] \quad SC = BA_{aspen} / BA_{total}$$

The main objectives of this study were to model aspen SC changes over time, to assess aspen successional pathways in boreal mixedwoods, and to enhance the understanding of aspen growth and yield under different conditions to improve aspen management and utilization.

Material and Methods

After analyzing various model forms, two base models were chosen for use in this study:

$$[2] \quad y = \frac{c_0}{1 + \exp[f(x)]}$$

$$[3] \quad y = \frac{c_0}{1 + \exp[f(x)]} + \frac{1}{1 + \exp[f(x)]}$$

where c_0 is a parameter and $f(x)$ is often a linear combination of the independent variable matrix x . Both models could be considered as variations of the logistic-type function (Monserud 1984).

Using [3] as an example, any two SC-age data points on the same trajectory can be expressed as:

$$[4] \quad SC_1 = \frac{c_0}{1 + \exp[f(age_1)]} + \frac{1}{1 + \exp[f(age_1)]}; \quad SC_2 = \frac{c_0}{1 + \exp[f(age_2)]} + \frac{1}{1 + \exp[f(age_2)]}$$

where SC_1 and SC_2 are SC at ages 1 and 2, respectively. Isolating c_0 and solving for SC_2 produce:

$$[5] \quad SC_2 = \left(SC_1 - \frac{1}{1 + \exp[f(age_1)]} \right) \cdot \frac{1 + \exp[f(age_1)]}{1 + \exp[f(age_2)]} + \frac{1}{1 + \exp[f(age_2)]}$$

Since SC dynamics were found to be affected by site quality, site index (SI, top height at 50 years breast height age) was also incorporated into the model. Numerous expressions for $f(x)$ were evaluated. The final model is shown in [6], where $bhage$ refers to breast height age:

$$[6] \quad SC_2 = k \cdot \frac{1 + \exp[b_1 + b_2bhage_2 + b_3 \ln(1 + SI)]}{1 + \exp[b_1 + b_2bhage_2 + b_3 \ln(1 + SI)]} + \frac{1}{1 + \exp[b_3 + b_2bhage_2 + b_4 \ln(1 + SI)]}$$

$$k = (SC_1 - 1 / (1 + \exp[b_3 + b_2bhage_1 + b_4 \ln(1 + SI)]))$$

Following the same difference equation method, an alternative SC model was derived from [2]:

$$[7] \quad SC_2 = SC_1 \cdot \left(\frac{1 + \exp[1 + b_1SC_1 + b_2bhage_1 + b_3 \ln(1 + SI)]}{1 + \exp[1 + b_1SC_1 + b_2bhage_2 + b_3 \ln(1 + SI)]} \right)$$

Repeatedly measured permanent sample plot (PSP) data collected by the Alberta Government (Figure 1) were used to develop the models. Summary statistics for SC and other relevant variables describing the stand characteristics and measurement intervals were obtained.

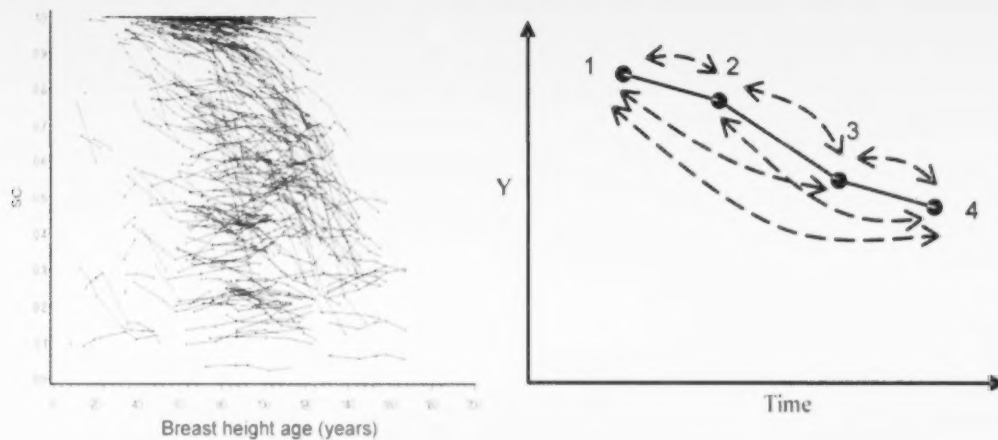


Figure 1. Left - observed aspen species composition trajectories from PSPs. Right - an illustration of potential growth intervals (dashed line) from a PSP trajectory, where 1, 2, 3 and 4 indicate measurement times.

Both [6] and [7] can be written in a more generic form as $SC_2 = f(SC_1, time_1, time_2, SI)$. The parameters of such a model can be estimated from PSP data, using one of the six data structures illustrated in Figure. 1 and detailed in Huang (1997) and Wang et al. (2004). In this study, all possible combination of growth intervals, including both forward and backward directions, were used for estimating model parameters. The estimation was carried out using the SAS/ETS MODEL procedure. The Gauss-Newton method was applied. Residual plots were examined. The potential problems associated with correlation and/or heteroskedasticity originating from difference equation formulations and PSP data were also investigated.

Results

Table 1 lists the parameter estimates and associated fit statistics for eqs. [6] and [7]. All estimates were significant at $\alpha = 0.05$. The R^2 values were high and the root mean squared errors (RMSE) were small. Residual plots indicated no obvious under- and/or over-predictions. All suggested good fits by the models. More elaborate model fitting techniques accounting for the correlated and/or heteroskedastic error structures showed that the benefits of these techniques had little practical significance, although further assessments based on independent data sets would be desirable. Site index was found to have a significant impact on SC changes over time, as depicted by the fitted models in Figure 2.

Table 1. Parameter estimates and associated fit statistics for eqs. [6] and [7].

Equation	n	b_1	b_2	b_3	b_4	RMSE	R^2	R^2_{adj}
[6]	5342	2.2525	0.02778	2.8212	-2.5152	0.0688	0.9421	0.9420
[7]	5342	-1.7324	0.02237	-1.2077		0.0684	0.9427	0.9427

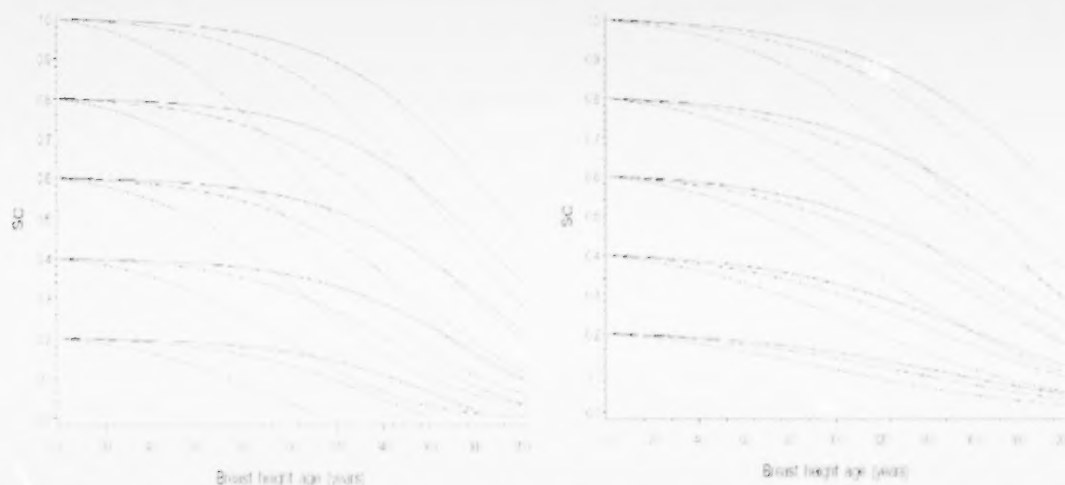


Figure 2. Fitted aspen species composition (SC) curves from eqs. [6] (left) and [7] (right), on three sites with site index values of 10 (dotted lines), 18 (dashed lines) and 25 m (solid lines).

Discussion and Conclusion

Although both [6] and [7] fitted the data well, [7] was finally chosen. It had a lower RMSE, a higher R^2 , and was more parsimonious than [6]. This choice had some interesting connotations. Traditionally, it was generally accepted that, in boreal mixedwood stands mainly consisting of aspen and white spruce, the shade intolerant aspen has a competitive advantage over spruce in the early stand development stage due to its faster early growth. As a result, aspen tends to rapidly establish dominance on the site by occupying the upper layer of the canopy. Shade tolerant spruce usually exhibits slow juvenile growth. As time progresses, the competitiveness of aspen is reduced relative to that of spruce as aspen starts to die around 80 years of age, allowing the shade tolerant spruce to reach the upper canopy and become dominant. The aspen component was usually assumed to break-up and to largely disappear after 120 years of age.

Surprisingly, as shown by the data (Figure 1) and from the results of the modelling, a majority of aspen stands do not disappear. They hang in there beyond 120 years. The likely reason for this is that, gaps created by the mortality of the original aspen cohort appear to be replaced in time by new aspen suckers, which eventually form part of the main canopy. This replacement process continues through a gap opening-and-closing cycle, determined by the initial aspen species composition, site quality, competition from the spruce, age and other stand characteristics. It has some important biological, silvicultural and regulatory implications.

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An Analysis Framework for Developing SFM-Based Regeneration Standards

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Introduction

Forest management is the art and science of balancing the flow of extractive goods and services with maintaining the forest as a whole in a desirable state. Every management action undertaken should ultimately be linked to some vision of this balance (the forest management objectives). As part of the forest management process, we must identify how individual activities impact on future stand structures, and be cognizant of how local structures are summed at the landscape unit and larger scales.

Assessing the contribution of individual stands to the larger forest condition (as quantified by forest landscape objectives) is often fraught with uncertainty, particularly at an early age. From regeneration to maturity, forest stands undergo massive changes. Given this uncertainty and the fact that our largest opportunity to shape future forest condition occurs at the harvest and reforestation stages, it is critical that we know the conditions to create in young stands (the reforestation objectives) such that our forest landscape objectives are likely to be achieved.

The Analysis Framework

An analysis framework has been developed, composed of the following steps, for defining reforestation objectives and measurement standards based on forest management objectives:

1. A range of juvenile stand conditions, representing a reasonable set of possible reforestation plans, is generated within a newly developed *silviculture survey simulator*.
2. Each potential stand is evaluated within the simulated framework using one or more existing and/or proposed survey metrics.
3. Random samples from the simulated stand are used as treelists or stem maps to initiate projections of future stand conditions using existing growth models.
4. Projected stand conditions are compared to desired conditions, and assessed either for success/failure or placed into classes reflecting a range of desired conditions.
5. Reforestation metrics are correlated to measures of desired future outcomes.

The framework described here is similar in principle to a process formerly applied successfully for simply structured conifer stands by Bergerud (2002). It is intended to form part of a larger program of adaptive management, whereby management practices are continuously vetted and improved as better tools and techniques are found, and ongoing monitoring of outcomes indicates the degree to which initial predictions are accurate.

The Silviculture Survey Simulator

The stand level silviculture survey simulator is being built within the Microsoft Excel environment using the VBA programming language. The simulator is intended to operate at the scale of typical harvest openings, to include a diversity of commonly used and proposed survey plot options, and to encompass a wide range of tree species and spatial diversity.

Stand structures in the model are controlled using a combination of multi-scale horizontal complexity layers, species composition, and vertical stratification. Contributing to horizontal structure are features such as terrain or ecosystem units, linear features such as skid trails, and a variety of mapable patches representing discrete clumps, voids or competing vegetation. In various combinations, these features can be used to generate most stand structures that might be found in regenerated stands in temperate forests.

Proof-of-Concept Study

In the boreal mixedwood region of northeastern British Columbia, licensees and government have defined landscape level species composition targets based on occurrence of various stand types. To ensure continued achievement of these targets, each regenerating stand must be evaluated for its future composition by timber volume, classified appropriately, and tallied by area in a ledger system. In this manner, regenerating stand types that are surplus to needs relative to landscape targets can either be avoided through appropriate application of harvest and silviculture systems, or identified early and treated to achieve a more desirable condition.

Within this system, intimate mixtures of aspen and spruce have been particularly problematic, as there were no survey-based metrics recognized as reliable indicators of future outcomes. In particular, the strong patterns of succession in these stands made early measurements difficult to relate to long-term development. The analysis framework described above was employed to explore development of appropriate survey systems and predictive thresholds.

Thirty six simulated stands, each representing 25 ha, were generated in the survey simulator. The spruce component of each stand was held constant, assuming planting at a density of 1200 trees/ha with 10% random mortality. Aspen composition was varied based on percentage of the total area covered by dense patches of suckers (10 to 90% in 10% increments), and on density of individual aspen in areas not covered by clumps (0, 200, 400 and 800 trees/ha with random spacing). Initial tree heights were drawn from normal distributions: mean aspen height was 3.0 m with a standard deviation of 0.6 m; mean spruce height was 1.2 m with a standard deviation of 0.2 m. Spruce heights were then adjusted downward to account for localized patterns of suppression from overtopping aspen, and diameters for both species were predicted from height and local measures of stand density.

For each stand, a composite yield table was generated from 36 separate simulations using the Mixedwood Growth Model (MGM)². Each simulation represented local competitive conditions at a random location within the highly variable stands. This approach was required to adequately account for spatial variability using an individual tree model that is not spatially explicit.

Each simulated stand was also sampled using 36 survey plots on an 80 m grid with a random starting point. Plots followed a variation of a mixedwood survey methodology proposed by Phil Comeau at the University of Alberta. In this system, the main plot has a radius of 3.99 m, and is divided into quadrants on N-S and E-W axes. Quadrants are tallied as unstocked, aspen, spruce or mixed based on presence of acceptable trees. For each spruce tree in the main plot, a tree-centered subplot is established with a radius of 5 m, and divided into quadrants with axis orientations so as to maximize the cumulative distance to the nearest aspen in each of the 4 quadrants. For a spruce to be considered acceptable, the minimum

distance to any aspen is 2 m, with a minimum cumulative distance of 14 m.

The value of results from this survey as a predictor of future outcomes is illustrated in Figure 1. It appears that the tested survey metric is a reasonable indicator of species composition by merchantable volume at age 80. Planned work to expand on this proof-of-concept case study includes replication using other growth models such as SortieND or TASS 3, inclusion of a wider range of spatial patterns, tests for required survey intensity to satisfy precision needs, and tests of alternate and preferably simpler survey methodologies that might provide similar results.

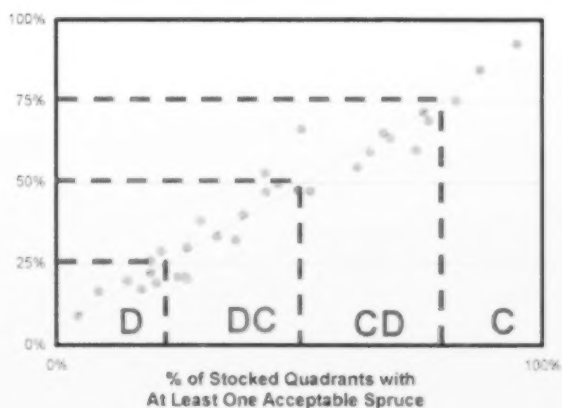


Figure 1. A relationship between the calculated survey metric and predicted species composition is useful for setting reforestation standards. If, for example, a management objective required a minimum conifer component at harvest of 40%, a corresponding threshold level for the silviculture survey statistic could be determined, such that most stands complying with the survey standard would also meet the management objective. In the current case study, the relationship is used to classify stands based on percent of conifer merchantable volume in the projected stand at age 80: 0 to 25% (D), 25 to 50% (DC), 50 to 75% (CD) and 75 to 100% (C).

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² MGM is an individual tree, distance independent growth model developed by Steve Titus and colleagues at the University of Alberta.



Measuring Complexity I

Concepts of Measuring and Reconstructing Spatial Woodland Structure

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Introduction

Structure is an important characteristic of forest ecosystems. There are three related concepts in biological structures, *self-organisation*, *structure/property relationships* and *pattern recognition* (Deutsch, 1994; Torquato, 2002; Wolfram, 2002). Inter tree competition, self-thinning and morphological differentiation can be understood as processes of self-organisation which are closely related to structure/property relationships, ideas already well known in material science, physics and geology (Torquato, 2002). Individual structural elements of a forest ecosystem, such as tree species and tree sizes, when arranged in different ways may result in very different expressions of the properties (e.g. growth, biodiversity or habitat functions) for the forest as a whole. Pattern recognition is the method of identifying distinctive spatial patterns and of linking them with the corresponding properties. The estimation and interpretation of tree diversity, competition indices and other point process statistics is a potentially powerful application of pattern recognition and many studies in growth and yield science show that structure determines processes on a short-term basis and processes modify structure on a long-term basis. Because of complex interactions between trees a full understanding of processes is possible only if detailed woodland structural patterns are known and knowledge of changing structural patterns can help to interpret the underlying processes (Pretzsch, 2002). In a similar way to the fact that understanding the internal structure of chemical compounds and materials allows their synthesis, so too a detailed knowledge of spatial woodland structure and processes allows woodland synthesis.

The objective of this paper is to give an overview of research concepts of measuring and reconstructing spatial woodland structure.

Review of Concepts of Estimating Spatial Woodland Structure

Early attempts to quantify spatial aspects of forests go as far back as 1835 (Illian et al., 2007) and since the 1950s attempts to formalise spatial relationships of trees in woodlands have seen the development of numerical indices with the aim of describing

spatial tree diversity (Stoyan and Penttinen, 2000; Pommerening, 2002). Spatial tree data can be thought of as multivariate data containing several types of information, e.g. species, age, size and distance to the nearest neighbour. These and other aspects of spatial tree data can be employed to systematise concepts of estimating spatial woodland structure. One way to do this is to subdivide data into three different categories, the diversity of tree positions, tree species diversity and the diversity of tree size (Gadow, 1999; Pommerening, 2002). Alternatively one can distinguish between the type of spatial neighbourhood, e.g. tree-based, point-based neighbourhoods (Gadow and Hui, 2002), absolute nearest neighbour, nearest species neighbour, mutual nearest neighbour, which have similarities with the nearest neighbour methods used for computing missing data (LeMay and Temesgen, 2005). Some concepts of spatial quantification are based on the nearest neighbour concept, others like the correlation functions (Stoyan and Stoyan, 1994; Diggle, 2003) quantify the relationship between one tree and all other trees within a window of observation. Some concepts specifically focus on the quantification of small-scale spatial aspects of individual trees such as competition indices (e.g. Moravie and Robert 2003; Bauer et al., 2004), while others are designed to deliver summary characteristics for the forest as a whole. Even among the group of nearest neighbour indices there are different construction principles, which are reviewed in Illian et al. (2007). All these different approaches are more or less useful depending on the specific analysis context and may have far-reaching consequences such as the question of edge correction and statistical testing.

Despite the conceptual differences all approaches are based on the idea of (marked) point processes. Point process statistics are concerned with the analysis of discrete variables, i.e. innate characteristics which can be defined only at the location of the points which form the process, for example the diameter of a tree. Trees are represented by points and marks, the points give the locations of the trees, the marks characterise the trees further, e.g. their species, size or shape. In contrast to geostatistical analysis point process statistics deal with situations where the points and marks are not independent. The main aim of point

process statistics is to understand and describe the short-range interaction between points and may help to model these interactions (Illian et al., 2007; Diggle, 2003).

With any spatial estimator the treatment of edge trees, which are close to the boundary of the window of observation, can affect the estimation, since some of their neighbours are likely to fall outside the window. Strategies of compensating edge bias are dependent on the estimator type (Pommerening and Stoyan, 2006). Trends of edge bias effects are presented in the paper.

Review of Concepts of Reconstructing Spatial Woodland Structure

Reconstruction methods allow the synthesis of the original woodland structure from measures of spatial woodland structure. This group of techniques reproduces woodland structures, which have the same statistical properties as the original sample (Torquato, 2002; Tscheschel and Stoyan, 2006). Instead of merely analysing spatial forest structure, reconstruction reverses the process and actively synthesises tree patterns numerically (Pommerening, 2006). This can be useful in evaluating the statistical power of spatial measures by investigating how much they contribute to the synthesis. Another application of reconstruction methods is modelling situations where individual tree coordinates are required as input data for simulation runs or visualisations. Reconstruction methods can also be employed for edge bias compensation where tree patterns similar to those inside a window of observation are simulated around the edges. The artificial synthesis of forest structure could also be used by conservationists who wish to develop forest landscapes to create particular habitat patterns in order to support or re-introduce rare animal species. Reconstruction methods can be subdivided into parametric and non-parametric approaches and include point process models, cellular automata and simulated annealing (Pommerening and Stoyan, 2007).

Discussion and Conclusions

Point process statistics are tools assisting pattern recognition and are a relatively new branch of spatial statistics. They have found a wide range of applications in various fields of natural sciences among which biological and forest sciences are the most prominent (Stoyan and Penttinen, 2000; Diggle, 2003; Illian et al., 2007). The huge variety of different approaches is reflected by the systematics introduced in this paper. Investigating common ground and differences helps

to understand which approaches are appropriate in which analysis context. It also demonstrates that some concepts such as those of structural and competition indices are often not so dissimilar to each other than commonly believed. In most cases the choice of estimators has consequences for the estimation process such as statistical testing and edge correction (Pommerening and Stoyan, 2006).

Successful modelling and reconstruction results demonstrate that it is possible to go a step beyond the mere analysis of spatial tree patterns. Reconstruction experiments highlight that not only the successful analysis but also the synthesis of spatial structure depend on the correct choice of spatial statistics and that this choice is different from woodland to woodland. Reconstruction methods can potentially also be employed to correct sampling results.

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Measuring Canopy Structural Components From Leaf-off and Leaf-on Laser Imaging

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The objective of this study was to develop detailed 3D canopy structural measures from ground-based LiDAR range imagery. A specific goal was to quantify the amount and arrangement of leaves and wood elements separately by comparing images taken at different points in time. Multi-view LiDAR imagery was acquired at paired locations in a deciduous, broadleaved natural forest in the southern Appalachian Mountains of western North Carolina,

U.S.A., during leaf-off and leaf-on conditions in winter 2001 and summer 2002. Range images were aligned simultaneously across space and time based on matched tree bole section segments extracted from point clouds. The resulting point clouds provided detailed data for quantifying canopy structure in 3D. Plant element separation and 3D structural measures depended on image alignment accuracy and scene occlusion. Gains from using multi-view and multi-temporal imagery were investigated.

Evaluating Effective Leaf Area Index in Complex Stands Without Outside Reference

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Introduction

Leaf area index (*LAI*), a value widely used to describe forest stands, has traditionally been estimated from the observed relative irradiance in a stand. Forests have extensive height and spatial ranges, making it difficult to reach the "outside" of the forest during sampling. I propose a method to estimate *LAI* by using the ratio of near-infrared (*NIR*) to red irradiance (*RED*) under the forest canopy, with no reference to values outside the forest. A similar method devised more than 20 years ago, that used the ratio of average values of the whole field of view (*FOV*) of the irradiance detector, was examined by Jordan (1969), Szeicz (1974) and Norman and Jarvis (1974). They found that, though the ratio of *NIR* to *RED* was linearly relate to *LAI*, the slope of this relationship might vary with the canopy type and the approach would thus require calibration. My method uses the averaged ratios calculated at subdivisions of *FOV* (*SDF*) and was tested at four points in a complex secondary forest. I discussed the evaluation of relative irradiance (*RI*) by using the *NIR* to *RED* ratio.

Theory

To measure *RED* and *NIR*, previous researchers used detectors with wide-angle. If we suppose that the *FOV* consists of many *SDF*, then each *SDF* *i* registers *RED* as *sRED_i* and *NIR* as *sNIR_i*. The values of *RED* and *NIR* for the entire *FOV* represent the mean values for all *SDFs*:

$$RED = \frac{\sum_{i=1}^n sRED_i}{n} \quad (1)$$

$$NIR = \frac{\sum_{i=1}^n sNIR_i}{n} \quad (2)$$

where *n* is the number of *SDF* in the *FOV*.

Therefore the ratio of *NIR* to *RED* is;

$$NIR/RED = \left(\frac{\sum_{i=1}^n sNIR_i}{n} \right) / \left(\frac{\sum_{i=1}^n sRED_i}{n} \right) = \frac{\sum_{i=1}^n sNIR_i}{\sum_{i=1}^n sRED_i} \quad (3)$$

In contrast, the following equation calculates the average

$$NIR/RED = \frac{1}{n} \times \sum_{i=1}^n \frac{sNIR_i}{sRED_i} \quad (4)$$

Figure 1 illustrates the difference between Eq. 3 and Eq. 4. In this example, the *p* percent of the *FOV* represent sky, and the remaining represent plant (foliage, branch or bole). Sky *SDF* show high *sRED_i* and *sNIR_i* and consequently produce a low *NIR/RED* ratio, whereas plant *SDF* show very low *sRED_i* and low *sNIR_i* and consequently produce a high *NIR/RED* ratio. When *p* is only 1.0%, Eq. 3 underestimates the ratio by 40 %. I thus used Eq. 4 to estimate the *NIR/RED* ratio.

Site Description

We tested this method of evaluating *RI* and the resulting effective *LAI* in a secondary forest in Jokoji National Forest near Nagoya, Japan, on 17 days from March to November 2006. The forest was a closed-canopy, mixed stand of broadleaved trees, dominated by both deciduous trees (*Quercus serrata* Thunb.

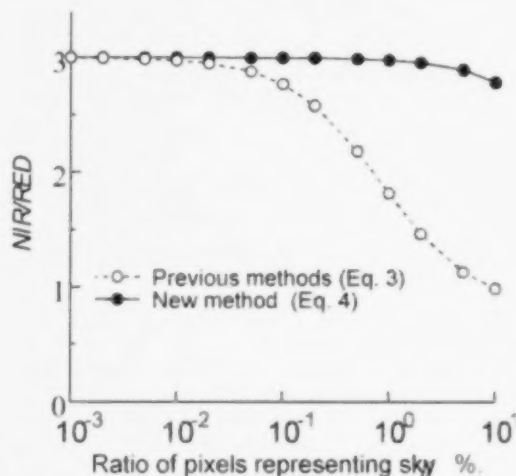


Figure 1. An example of the difference of the respective ratios of *NIR* to *RED* in each *SDF*: between previous methods and ours.

[QS] and *Evodiopanax innovans* (Sieb. et Zucc.) Nakai [EI]) and evergreen trees (*Ilex pedunculosa* Miq. [IP], *Symplocos prunifolia* [SP], *Quercus glauca* [QG], and *Pinus densiflora* [PD]). This paper presents the results of measurements at four observation points. Point 1 was located under a small gap surrounded mainly by large IP crowns and partly by QS. Points 2 and 3 were covered by equal amounts of QS and IP, and Point 4 was covered primarily by QS (up to 80%), with the remainder of the cover accounted for by IP and PD. The 3D structure of canopy above these points was measured by the laser plane rangefinding method after Tanaka *et al.* (2004), which projects a laser beam (near-infrared or red) onto an object such as the canopy and uses a camera to detect the illuminated trace of the beam on the image. Each point on the trace forms a triangle defined by the point, the laser projector, and the camera, and its position can thus be converted into 3D coordinates by means of triangulation. By this approach I reconstructed the 3D structure of the canopy by synthesizing a dataset captured looking downward from an 18-m-tall tower and three datasets captured looking upward from the forest floor.

Methods

The upward measurements were obtained by using a 150-cm-tall tripod at each survey point and a camera equipped with optical filters for NIR or RED. To compensate for the poor dynamic range of the camera, 12 exposure were obtained automatically at shutter speeds ranging from 1/10,000 to 2/5 s, and I selected the most suitable exposure for each pixel.

Results and Discussion

Figure 2 is a typical image of NIR (left) and NIR/RED (right) in the FOV. Higher values (bright white) represent a higher ratio, where lower NIR was measured. These parts of the FOV also correspond to a thicker canopy. By using a strong relationship between the NIR/RED ratio by Eq. 4 and *RI*, I evaluated effective LAI (Fig.3). In March (day of year [DOY] < 90), the deciduous trees had no foliage, so effective LAI was low. The foliage of the deciduous trees expanded until mid-May. The exclusion of windy days reduced the number of points, especially between DOY 110 and 160 and DOY 214 and 305, but visual examination confirmed that there was no rapid phenological change during these periods.

Conclusion

I proposed a method which uses the averaged NIR/RED calculated at SDF and found the seasonal change in resultant effective LAI appeared reasonable.

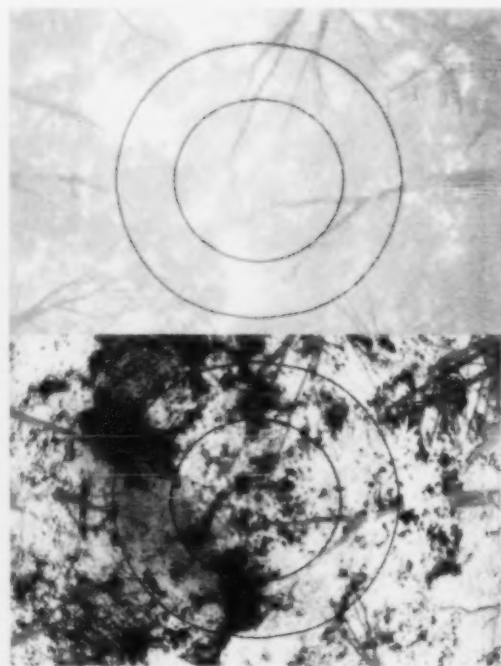


Figure 2. Sample NIR (left) and NIR/RED (right) images of the FOV (looking upward at survey point 3 on 3 July 2006). The black distorted circles represent the zenith angles: the inner circle represents 16.7 degree; the outer 28.6 degree.

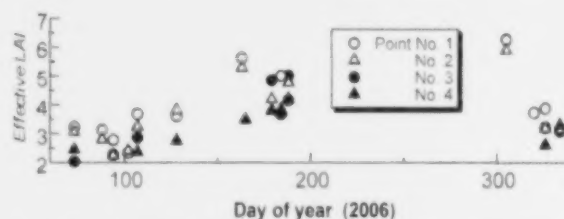


Figure 3. Fluctuations of effective LAI determined from NIR/RED by Eq. 4.

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Spatial Scale Affects Diameter Distribution Shape in Uneven-Aged Northern Hardwoods

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Introduction

Uneven-aged management techniques rely on the control of stand structure using small group and single-tree selection systems. Selection systems are perceived to approximate the primary natural disturbance regimes associated with the development of multi-cohort forests. For example, in old-growth northern hardwood forests > 50% of trees enter the canopy by utilizing canopy gaps created by low intensity disturbances that remove less than 20% of the canopy (Frelich and Lorimer 1991).

Diameter distributions (number of trees graphed by diameter class) can be used to produce "balanced" forests where each diameter class is allocated an equal amount of growing space and overall management is thought to be sustainable (Meyer 1952, O'Hara 1996). Early work highlighted the prominence of a negative exponential distribution shape in old-growth forests (de Liocourt 1898, Meyer 1952). Since this distribution formed under natural processes and is present in self-perpetuating forests (Leak 1996, Crow et al. 2002) it became the ideal for management. This shape has also been observed in stands managed under single-tree (Leak 1996, Crow et al. 2002) and group/patch (Leak and Filip 1977,

Leak 1999) selection (Figure 1). However, a rotated sigmoid distribution shape has also commonly been observed in both old-growth and managed uneven-aged stands (Goff and West 1975, Leak 1996, Goodburn and Lorimer 1999, Leak 2002, Schwartz et al. 2005).

Northern hardwood forests are dominated by shade-tolerant species that are perpetuated by gap-phase disturbances resulting in the development of multi-cohort stands, making this an ideal system for investigating population structure of complex stands (Eyre and Zillgitt 1953, Arbogast 1957). Our specific objectives in this study were to: (1) determine how the sample area used to construct diameter distributions influences the interpretation of distribution shape, and (2) examine differences in distribution shape between managed and unmanaged stands.

Materials and Methods

We examined stand structure and diameter distribution shape in uneven-aged northern hardwood stands of the western Upper Peninsula of Michigan. Four study sites were located in unmanaged old-growth: Isle Royale National Park, Porcupine Mountains Wilderness State Park, Sylvania

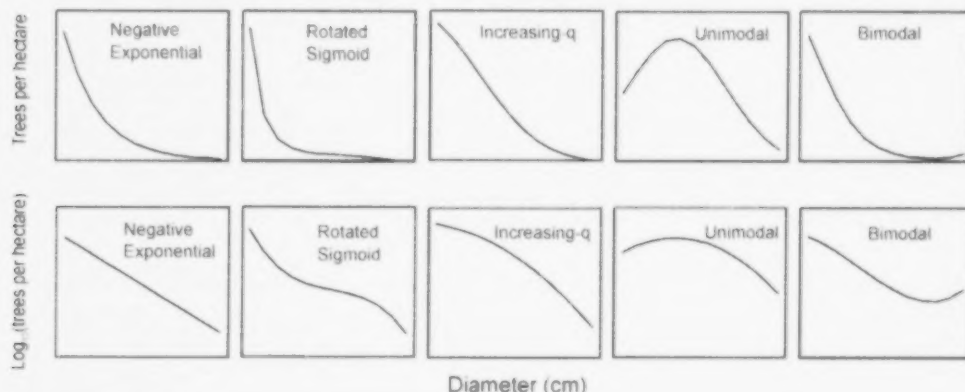


Figure 1. Diameter distribution shapes typically observed in uneven-aged northern hardwood stands in western Upper Michigan.

Wilderness Area, and the Research Natural Area at the Upper Peninsula Experimental Forest. Three study sites were located in managed northern hardwood stands owned by the Michigan Department of Natural Resources and the Ottawa National Forest. At each site, a square 3.2-ha plot was established; each 3.2-ha plot contained a grid of 64 0.05-ha subplots. Subplot number, tree species, and diameter at breast height (dbh; 1.37 m) were recorded for all trees ≥ 3.0 cm dbh and greater. To categorize diameter distribution shape, the base 10 logarithm of the tph was regressed versus all combinations of the 5-cm diameter class midpoint (DBH), DBH^2 , and DBH^3 . The best fitting model was selected from significant models ($P < 0.05$) based on the highest adjusted- R^2 and lowest RMSE values. Distribution shape was determined by examining the model variables present, as well as by the sign of the model coefficients. Five distribution shapes were observed. To determine the effect of sample area, diameter distributions were developed for each site at multiple spatial scales by aggregating subplots—0.05, 0.2, 0.4, 0.8, 1.6, and 3.2 ha.

Results

The increasing- q and unimodal shapes were only observed in managed stands, regardless of spatial scale (Table 1). The increasing- q pattern was dominant in managed stands, where it made up 44% of all observed distribution shapes. Unmanaged stands had larger proportions of rotated sigmoid, negative exponential, and bimodal shapes than managed stands, with 50% of distributions being rotated sigmoid. At the largest scale examined (3.2 ha), distributions of managed stands were 67% increasing- q and 33%

rotated sigmoid in form, whereas unmanaged stands were 25% negative exponential and 75% rotated sigmoid. Nevertheless, there was only weak statistical support for differences in stand structure between managed and unmanaged stands at that scale ($G = 5.06$, $df = 2$, $P = 0.080$).

In managed stands, distribution shape showed no association with spatial scale ($G = 16.32$, $df = 20$, $P = 0.696$), and the increasing- q , bimodal, and unimodal distribution shapes were each observed in one stand at sample areas of 0.4 to 1.6 ha (Table 1). At the 3.2-ha scale, increasing- q was the dominant pattern in managed stands. Conversely, distribution shape varied significantly with the spatial resolution used ($G = 26.37$, $df = 15$, $P = 0.034$). As spatial scale increased, the bimodal shape no longer occurred, and the rotated sigmoid distribution shape became dominant. Negative exponential shapes were also observed at the larger spatial scales, comprising up to 25% of the unmanaged distributions. The use of a small spatial scale (0.05 ha) yielded inconsistent results in both managed and unmanaged stands (Table 1).

Discussion

In this study, we observed five diameter distribution shapes in uneven-aged northern hardwood stands. Managed stands displayed a wider variety of distribution shapes and were most likely to have an increasing- q shape, while unmanaged old-growth stands frequently exhibited rotated sigmoid diameter distributions. Sampling scale influenced the interpretation of distribution shape, with the strongest effect observed in unmanaged stands. Collectively,

Table 1. Proportional representation of diameter distribution shapes.

	Sample Area (ha)					
	0.05	0.20	0.40	0.80	1.60	3.20
Managed						
Negative Exponential	0.00	0.00	0.00	0.00	0.00	0.00
Rotated Sigmoid	0.00	0.00	0.33	0.33	0.33	0.33
Increasing- q	0.33	0.67	0.33	0.33	0.33	0.67
Bimodal	0.33	0.33	0.00	0.00	0.00	0.00
Unimodal	0.00	0.00	0.33	0.33	0.33	0.00
Non-significant	0.33	0.00	0.00	0.00	0.00	0.00
Total	1.00	1.00	1.00	1.00	1.00	1.00
Unmanaged						
Negative Exponential	0.00	0.50	0.50	0.00	0.25	0.25
Rotated Sigmoid	0.00	0.25	0.25	1.00	0.75	0.75
Increasing- q	0.00	0.00	0.00	0.00	0.00	0.00
Bimodal	0.50	0.25	0.25	0.00	0.00	0.00
Unimodal	0.00	0.00	0.00	0.00	0.00	0.00
Non-significant	0.50	0.00	0.00	0.00	0.00	0.00
Total	1.00	1.00	1.00	1.00	1.00	1.00

our results suggest that a sampling intensity of 13 to 25% of stand area (3.2 ha in this case) may be needed to reliably characterize stand structures using diameter distributions. Greater sampling intensity may be needed in unmanaged stands as a result of higher spatial heterogeneity in stand structure than found in managed stands.

Although the literature points toward the presence of negative exponential stand structure at large spatial scales, we did not observe a transition towards a negative exponential structure. However, at greater spatial scales than used in this study, a general trend towards the negative exponential pattern may still occur, especially where multiple stands are combined.

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Modelling the Spatial Dynamics of Regeneration in Mixed Stands

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Introduction

The natural regeneration of tree species is one of the key processes in the development of complex stand structures. Due to the wide range of adaptation mechanisms and the large number of factors which come into play during the regeneration process, research has been oriented towards single-factor analyses instead global-process models. Spatial pattern analysis tools have proved useful for studying the regeneration process in forest stands. These techniques can be employed to analyse the relationship between the spatial distribution of environmental variables (such as light or substrate conditions) and the recruitment pattern (Denslow and Guzmán 2000, Pardos *et al.* 2007), or the spatial interaction between the different strata and species (Montes and Cañellas 2007, Moer 1998). Henceforth, these spatial interactions might be incorporated into a natural regeneration model. This study focuses on the application of a spatial regeneration model to evaluate natural regeneration within the pinewood-broadleaved forest ecotone in south-western locations of Scots pine.

Material and Methods

Study Site

The study site comprises three locations in the central Mountain Range of Spain in the ecotone between Scots pine (*Pinus sylvestris* L. and Pyrenean oak (*Quercus pyrenaica* Willd.) forests (at altitudes of approximately 1200 m), each having different ecological and management characteristics: *Hoyocasero*, an isolated Scots pine population in the western area, and *Valsain* and *Rascafría*, in the middle of the Central Mountain Range, where the widest spread of Scots pine stands in central Spain has developed. Five experimental plots of 25 m radius forming a transect across the ecotone were established in each location. DBH of the trees was measured and those with DBH above 7.5 cm were mapped in each plot and classified according to species and stratum (mature if DBH $\geq$ 25 cm or newly established if DBH < 7.5 cm).

Spatial Regeneration Model

The spatial regeneration model generates the quantile bounds of the $L(d)$ function (Besag, in Ripley 1977)

for a chosen quantile and number of simulations for each species and strata, as well as the $L_{12}(d)$ function (Dale 1999) for the different pair wise combinations. The initial state may be either simulated as a pure or mixed mature stand with trees randomly located or a given mapped plot. Tree mortality gradually opens gaps in the initial stand. This process might allow the large scale structure of the upper strata in the real plot to be maintained. An establishment subroutine is run for each element removed from the upper stratum. Seed regeneration is randomly established, whereas sprout regeneration or new seedlings appear around the individuals of sprouting species or those species whose new seedlings benefit from the proximity of others already established within a given distance (facilitation radius). Above a given competition threshold (different for each species and type of regeneration), the likelihood of seed and sprout establishment is inversely proportional to the competition (in tree number or a competition index) calculated over different distances for each previous strata and recruitment species. The seed establishment subroutine was iterated by using a dispersal capability factor different for each species.

If the regeneration process in the experimental plots was defined by the model parameters, the quantile bounds generated should contain the experimental $L(d)$ and $L_{12}(d)$ functions. As the analysed plots only contain Scots pine in the upper stratum, a 400 stem/ha Scots pine stand was chosen as the starting point. 99 simulations were carried out for each set of parameters and for each experimental plot, straining the resulting species composition to the current composition of the plot. The 95% quantiles of 99 simulations were generated for each experimental plot and the shape of the experimental function and the interval defined by the quantiles were compared to iteratively adjust the model parameters.

Results

Figure 1 shows the 95% quantile bounds for the 99 simulations and the experimental $L(d)$ and $L_{12}(d)$ functions for one of the mixed plots in *Rascafría*. The true pattern of the upper stratum was within the range of the final pattern simulated (Figure 1.a). A tree number threshold for Scots pine seed establishment and Pyrenean oak seed and sprout establishment of

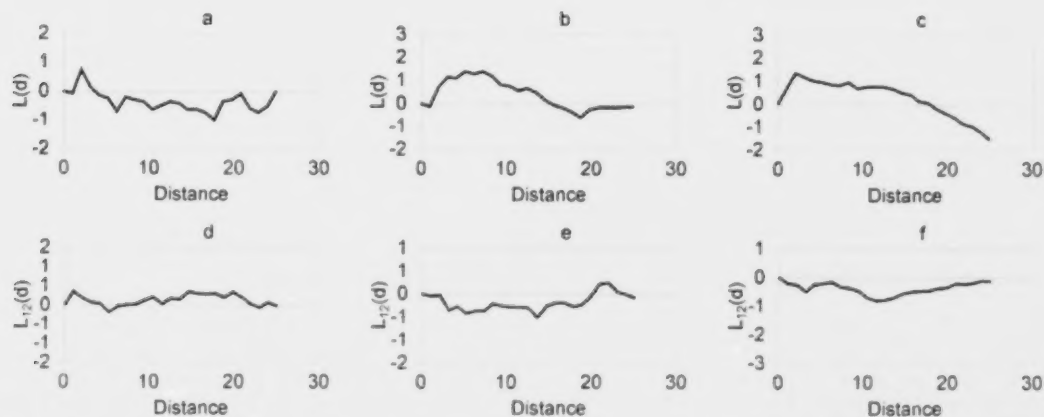


Figure 1. Empirical and 95% quantiles of 99 simulations of the regeneration model $L(d)$ function for a) Scots pine upper stratum, b) Scots pine regeneration and c) Pyrenean oak regeneration, and intertype $L_{12}(d)$ function d) upper stratum-pine regeneration, e) upper stratum-oak regeneration and f) pine regeneration-oak regeneration.

0.115, 0.180 and 0.080 stems/m² respectively gave the model results that best matched the experimental functions. The seed dispersal capability; Scots pine/Pyrenean oak ratio was 20. The distance of competition from the upper pine strata was 20 m for pine regeneration and 9 m for oak regeneration, whereas the distance of competition with the younger stratum was 12 m for the pine regeneration and 6 m for the oak regeneration. The $L(d)$ function shows that the quantiles reflect aggregation at short scales but regular distribution at a larger scale for both pine and oak regeneration (Figure 1.b and 1.c). The $L_{12}(d)$ quantiles for the upper stratum with pine and oak regeneration, as well as between regeneration of both species, also fit quite well the experimental function, which describes spatial repulsion from the upper strata at short scales for oak regeneration and spatial independence for pine regeneration (Figure 1.e and 1.d respectively) and repulsion at larger scales between both pine and oak regeneration (Figure 1.f).

Discussion

In this paper, a model for the regeneration process in mixed stands, which allows the structure derived from it to be compared with the current distribution of the trees, is presented. The dispersal capability of the species and its tolerance to competition from different species, as well as the scale of competition and facilitation processes can be analysed through this model. Differences between seedlings and sprouts in terms of tolerance to competition can also be assessed.

The mosaic of single-species patches characterizes the spatial pattern of the *P. sylvestris* and *Q. pyrenaica* stands in the ecotone of the Central Mountain Range. This structure may be the result of interaction between

the environmental heterogeneity and the different reproductive strategies and ecological requirements of both species highlighted by the regeneration model presented in this study. In fact, a dynamic equilibrium of single species patches should result from the coexistence between a species with efficient seed dispersal (such as *Pinus sylvestris* in this study) and a competition tolerant species (such as *Quercus pyrenaica*) (Pacala and Levin 1997, Murrell and Law 2003). This model can be used to assess the effects of different silvicultural alternatives on stand's regeneration and help to elaborate management strategies.

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Assessing the Population-Averaged Diameter Distribution and Its Variability

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Introduction

Foresters are used to relying on diameter distributions for decision making in forest management. However, the diameter population of a particular stand is usually too large to be entirely measured. As a consequence, the diameter distribution must be estimated from diameter samples and statistical inferences. In this summary, we present an estimator for the parameters of Weibull-distributed diameter populations.

Method

A set of 20 sample plots located in a single stand of mixed hardwood species provided a real-world case study. The stand diameter population was assumed to follow a two-parameter Weibull distribution. Random effects were specified to account for the plot grouping. These features yield the following likelihood function (Pinheiro and Bates 2000, p.62):

$$[1] \quad L(\alpha, \beta, \delta | \mathbf{y}) = \prod_{i=1}^{20} \int p_i(\mathbf{y}_i | \alpha, \beta, \mathbf{u}_i) p_2(\mathbf{u}_i | \delta) d\mathbf{u}_i$$

for $i = (1, 2, \dots, 20)$

where $\mathbf{y}$ is the vector of diameters, $p_1(\mathbf{y}_i | \alpha, \beta, \mathbf{u}_i)$ is the density of a Weibull distribution with α and β being the shape and the scale parameter, respectively, and $p_2(\mathbf{u}_i | \delta)$ the density of a normal distribution with mean 0 and variance-covariance δ . The integral can be approximated by adaptive Gaussian quadrature (Pinheiro and Bates 1995), and a Newton-Raphson algorithm can then provide a maximum likelihood estimator for the parameters.

Equation [1] can be seen as a statistical model whose error term follows a Weibull distribution. Different random-effect specifications were tested. Akaike and Bayesian Information Criteria (AIC and BIC) were used for model selection. The goodness of fit was assessed with diagnostic plots such as presented in Lambert (1992). Trees were grouped into 2-cm diameter classes and the expected probabilities were compared with the observed proportions in the data set.

The properties of the estimator were tested through simulation. A thousand fictive data sets were

generated from a known population. The population parameters were then estimated for each individual data set. Coverages and mean biases for the parameter estimates were compared to the true population parameters.

Results

According to the information criteria, the "best" model uses a plot random effect on the shape and scale parameters, such that:

$$[2] \quad \alpha_i = b_1 + u_{i,1} \quad \beta_i = b_2 + u_{i,2}$$

where $u_{i,1}$ and $u_{i,2}$ are two plot random effects. There was no major departure from the assumed Weibull distribution.

The model can provide an estimated diameter distribution, and its variability is then obtained through Monte Carlo simulation. An example of Monte Carlo simulation is shown in Figure 1.

The tests on the properties of the estimator are shown in Table 1. Basically, the estimator provides unbiased estimates with nominal coverage for the parameters of the population distribution. However, the variances of the random effects are underestimated with biased coverage.

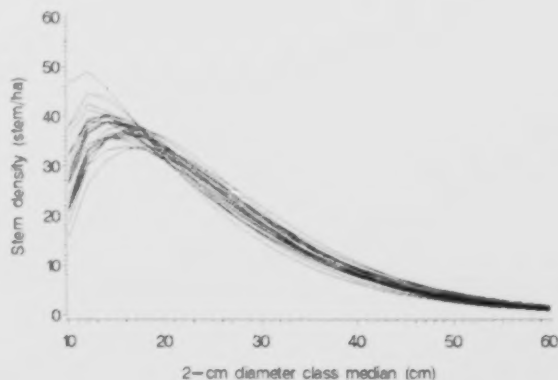


Figure 1. Example of the variability for the estimated diameter distribution.

Table 1. Mean bias and actual coverage of 95% intervals (computed from 1000 data sets drawn from a population with parameters $b_1 = 1.3$, $b_2 = 16.5$, $\delta_{1,1} = 0.06$ and $\delta_{2,2} = 8.9$).

Parameter	Mean bias (%)	95% confidence coverage
b_1	+0.4	96.1
b_2	+0.2	95.3
$\delta_{1,1}$ (variance of $u_{1,1}$)	-9.1	88.8
$\delta_{2,2}$ (variance of $u_{1,2}$)	-3.4	89.0

Discussion

Since there was no major departure from the assumption of a Weibull-distributed diameter population, bimodality observed at the plot level seems to be due to the sampling variability only. There is no evidence that a more complex function would provide a better fit.

The simulation also revealed that the likelihood estimator provides unbiased estimates for the model parameters and their variances. Consequently, the uncertainty of the estimated diameter population can be assessed as shown in Figure 1. However, the variances of the random effects tend to be underestimated. This problem of variance underestimation has already been outlined with multilevel generalized linear models (Breslow and Lin 1995; Browne and Draper 2006). Other estimators based on Bayesian approaches might prove more reliable in variance estimation.

Conclusion

Modelling diameter distributions is complex due to the data structure. This study proposes an estimator that produces reliable estimates at the population level when the assumption of a Weibull-distributed diameter population holds. The estimator enables a reliable uncertainty assessment for the estimated diameter population. The diameter distribution uncertainty should be considered in decision-making, especially in a partial cutting context. In fact, specific removals from each diameter class may not yield the expected residual diameter distribution just because of this uncertainty.

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Modelling the Spatial Structure of Complex Stands by Point Processes

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Introduction

There is a growing interest for complex - uneven-aged and /or mixed-forest stands. Unfortunately, due to their high complexity, the dynamics of these stands are more difficult to understand than those of pure and even-aged stands. Thus, new research questions have arisen in terms of stand description, stand dynamics and growth modelling.

As far as growth modelling is concerned, the use of individual based models (IBM) seems more appropriate, because of the individual variability within complex stands. Such models simulate the evolution of each individual tree according to its own characteristics and its local environment.

However, forest managers cannot easily use this kind of models, because it requires an initial state with the description and the location of each tree in order to run simulations. Such data are not commonly available. Consequently, forest researchers use virtual stands as initial state, and it is very important that those virtual stands be realistic, i.e. as close as possible to real ones.

Our aim is to present a model of spatial structure for oak-pine mixed stands that can be used to simulate realistic virtual stands. In this paper, we will present the 2 main steps of our modelling work (i) to characterize precisely the spatial structure of our real stands, in order (ii) to reproduce them accurately using point processes.

Analyzing the Spatial Structure of Oak-Pine Mixed Stands

Material

Our study focuses on mixed stands of sessile oak (*Quercus petraea*) and Scots pine (*Pinus sylvestris*) of the Orleans forest (France). For this work, we set up and mapped 25 1ha plots in irregular oak-pine mixed stands.

Methods

We analyzed the spatial structure of our oak-pine mixed stands. We used the classical Ripley function (Ripley 1977) $L(r)$, and intertype function (Lotwick and Silvermann 1982) $L_{12}(r)$ to characterise the specific spatial structure of each population, and the structure of the interaction between 2 populations.

Results

We synthesized the variety of identified spatial arrangement in a typology of oak-pine mixed stands based on spatial structure: In this paper we focus on the structure of canopy tree that corresponds to five main types (Ngo Bieng et al, 2006).

Figure 1 presents the spatial characteristics of one of our spatial type. Corresponding to 6 plots, this type is characterized by a structure not differing significantly from randomness for oaks (1a) and slightly clustered for pines (1b). We can notice the tendency to regularity of pines at small distances. The intertype structure (1c) is going from interspecific independence (for 2 plots), to interspecific repulsion at small distances.

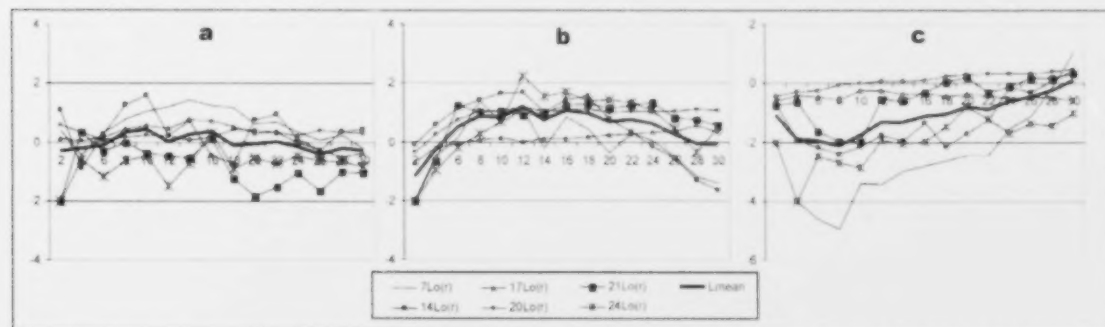


Figure 1. $L(r)$ function for oaks and pines in the canopy for type 3: (a) oaks, (b) Scots pines and (c) intertype $L_{12}(r)$ function. The mean curves are in bold.

Modelling the Spatial Structure of Oak-Pine Mixed Stands

Methods

We used point processes (Diggle 1983) to model the structure of the identified spatial types. For each type, we selected relevant point processes corresponding to the main spatial characteristics highlighted by the typology. The more relevant in our case are: the Neyman-Scott (NS) point process that simulate aggregated patterns; and the "Hard core" (HC) point processes, a pairwise interaction process in which distinct points are not allowed to come closer than a threshold distance.

First, we simulated the pine locations with an aggregated structure by the NS process. We added an additional constraint of distance between pines by the HC process to follow up the highlighted regularity at small distance. Second, we simulated randomly locations corresponding to oaks at a minimum distance from pines by the HC process to follow up the highlighted slight repulsion. Finally, this model has 4 parameters for a given density of pines and oaks: (i) the number of aggregates of pines (Nag); (ii) the radius of the aggregates (Rag); (iii) the minimum distance between pines (regularity distance, Dreg), (iv) the minimum distance between pines and oaks (repulsion distance, Drep).

We then fitted this model, in order that the Ripley and intertype curves of the virtual stands simulated by our model ($L^{sim}(r)$) be as close as possible the theoretical ones ($L^{real}(r)$) corresponding to the real spatial structure. We used the least square criterion defined in the equation below:

$$SCE = \sum_{i=1}^n [(L_{(1)}^{sim} - L_{(A)}^{real})^2] + \sum_{i=1}^n [(L_{(2)}^{sim} - L_{(B)}^{real})^2] + \sum_{i=1}^n [(L_{(1,2)}^{sim} - L_{(AB)}^{real})^2]$$

Results

The fitted parameters for the model are: (i) Nag=38; (ii) Rag=8; (iii) Dreg=10, (iv) Drep=4, corresponding to a least square criterion equal to 17.77. The figure 2 below presents the curves of 100 realisations of our model, and the mean simulated curve compare to the mean theoretical curve. The simulated patterns present the characteristics of the real one as we can see in the figure: a random distribution of oak, a slightly aggregated pattern for pine and an interspecific repulsion at small distances.

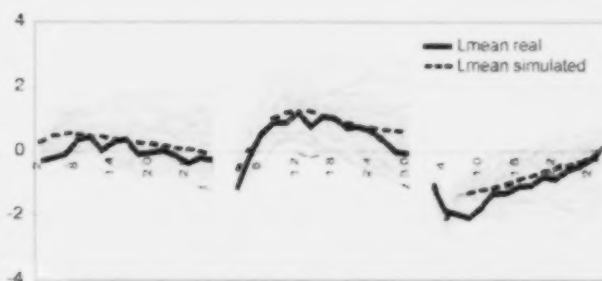


Figure 2. One hundred realizations of our model with the fitted parameters, Ripley functions $L(r)$ for oaks (left) and pines (middle) and the intertype $L_{12}(r)$ functions between oak and pine (right). The mean theoretical curves are in bold, the mean simulated curves are in bold and broken.

Discussion

In this paper we have presented a model of spatial structure that can be used to simulate realistic virtual oak-pine mixed stands. Those virtual stands could be used as initial state for the simulation proceed with an individual-tree-based growth model, that is used for growth modelling in mixed or irregular stands, in order to take into account the strong individual variability inside these stands (Pommerening 2006).

Moreover, this approach based on spatial structure supplies a clear description of mixed stands, and appears very important in a context of a lack of precise description of stands at a finer scale (McElhinny *et al.* 2005).

Conclusion

We succeed in building a virtual spatial structure having spatial characteristics close to the real spatial structure of our stands. We illustrated here for one of our spatial type, but we have done it for all the identified spatial types using different combinations of point processes. Our next step is to evaluate the realism of our simulations by comparing our simulated spatial structure to the spatial structure of other mapped oak-pine mixed stands, in the Orleans forest or elsewhere.

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Stochastic Gibbs Point Processes as Models for Forest Tree Spatial Pattern

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Introduction

A stochastic process is a sequence of random variables that are indexed by a reference set. In a forestry context, a collection of trees $\{x_1, x_2, \dots, x_n\}$ with spatial coordinates (x, y) is a stochastic point process, where each tree (considered as a point in space) is a random variable and the reference set is a subset of two-dimensional Euclidean space that is the spatial domain of interest. Gibbs processes are a special class of stochastic point processes that arose from the study of the thermodynamics of large particle systems in the field of statistical mechanics. In forestry applications, Gibbs processes are useful for they allow for the modeling of the interaction between trees so that trees inhibit each other as the trees become closer in space. Since trees have physical dimension and compete with each other, this type of a regular process appears suitable to simulate complex forest spatial patterns.

Materials and Methods

The data chosen to illustrate the use of Gibbs processes was drawn from the database of the USDA Forest Service's Coweeta Hydrologic Laboratory located in the Nantahala Range of the southern Appalachian Mountains in western North Carolina, U.S.A. (35.04°N, 83.45°W). The dataset consisted of five rectangular 80m x 80m plots (0.64 ha) stem-mapped plots that form the terrestrial gradient tree growth survey (Clark et al. 1998). The gradient plots were established along elevation and moisture gradients in two watersheds forested by uneven-aged, mixed hardwood stands, typical of forest ecosystems in the southern Appalachian Mountains. Species composition varied from cove hardwoods (*Liriodendron tulipifera* L.) to oak-hickory (*Quercus* spp., *Carya* spp.), and plot basal areas ranged from 22.84 to 35.56 m² ha⁻¹. Data utilized from the gradient plots consisted of plot coordinate location, species identification, and diameter at breast height (DBH) for trees measured in 1998. To focus on trees of at least merchantable size, the data were screened so that all trees were at least 10 cm diameter.

The Gibbs processes considered here are finite, simple point processes containing a fixed number of events $\{x_1, x_2, \dots, x_n\}$ occurring in a bounded region S that is a subset of two-dimensional Euclidean space. Formally,

a Gibbs point process is defined as a finite point process with a density that is the Radon-Nikodym derivative with respect to the homogeneous Poisson process (Møller and Waagepetersen 2004). Such a density can be constructed through specification of an interaction function controlling the spatial interaction between events of the process and a "chemical activity" function controlling the spatial intensity of the process. By restricting the interaction function to evaluate pairs of events, as opposed to triplets, quadruplets or larger collections, the class of pairwise interaction processes may be considered as a special case of Gibbs processes. Following the notation of Baddeley (2001) and Baddeley and Turner (2000), the probability density of the pairwise interaction process may be expressed as

$$f(\mathbf{x}) = \alpha \prod_{i=1}^{n(\mathbf{x})} b(x_i) \prod_{i < j} h(x_i, x_j)$$

where $b(x)$ is the chemical activity of the process, $h(x, x')$ is the interaction function, and the intractable constant $\alpha > 0$ is a normalizing constant that ensures that the density integrates to one.

The models proposed here are homogeneous Gibbs processes (Stoyan and Stoyan 1998). Intuitively this means that density of trees is considered to be spatially constant; mathematically this means that the processes are invariant to arbitrary translations and rotations of their events. In the context of pairwise interaction processes, this implies that the chemical activity function is a constant, β . Two models are considered for the interaction function, which are formulated in terms of pair-potentials $\phi(x, x')$ that are related to the interaction function through $h(x, x') = \exp[-\phi(x, x')]$. The first model, referred to as the exponential pair potential, is a variant of the pair potential explored previously by Fiksel (1984; 1988), Takacs and Fiksel (1986), and Penttinen, Stoyan, and Henttonen (1992). Unlike their model, the exponential pair potential does not impose a "hard-core" distance that prevents events of the process from being very close to each other. The exponential pair potential is defined as the following:

where $r = \|x_i, x_j\|$ is the distance between events of the process x_i and x_j , R represents the maximum distance where pairs of events still interact, and θ_1 and θ_2 are parameters. The second pair potential model is referred to as the modified exponential potential and is defined as

$$\phi(r) = \begin{cases} \frac{\theta_1}{r^2+1} + \theta_2 \exp(-\theta_1 r) & \text{for } r \leq R \\ 0 & \text{for } r > R \end{cases}$$

Restrictions are imposed upon the parameter space of these potentials to avoid unstable pair potential models that are highly attractive and result in Gibbs densities that cannot integrate to one (Gates and Westcott 1986). Specifically for the exponential potential, $\theta_1 > 0$ and $\theta_2 > 0$. For the modified exponential potential $\theta_1 \geq -2$, $\theta_2 > 1$, and $0 \leq \theta_3 \leq 1$.

To estimate the parameters of the Gibbs processes, maximum pseudo-likelihood (Besag 1975, 1977) will be employed. The Berman-Turner (1992) approximation to the pseudo-likelihood of a pairwise interaction process as described by Baddeley and Turner (2000) will be utilized; it avoids the intractable normalizing constant α by maximizing

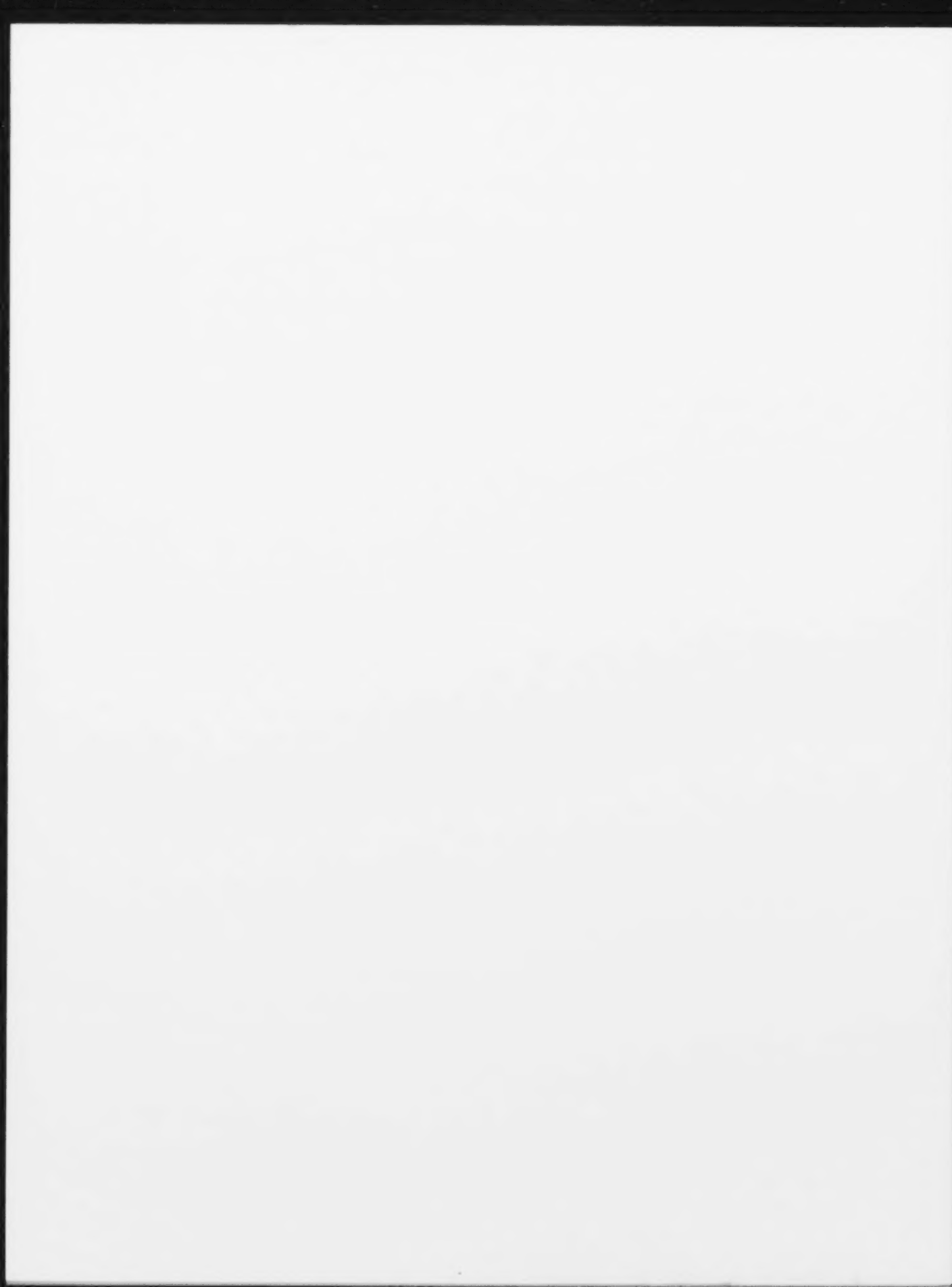
$$PL(\theta, \mathbf{x}) = \left(\prod_{i=1}^{(n)} h_i(x_i) \prod_{j=1}^{(n)} h_j(x_j, x_i) \right) \exp \left(- \int_{\mathcal{X}} h_u(u) \prod_{j=1}^{(n)} h_j(u, x_j) du \right)$$

where the integral in the above expression is numerically approximated by a quadrature scheme.

As Baddeley and Turner's approximation is designed for Gibbs processes whose conditional intensity functions are log-linear, the Gibbs models proposed here will be first considered when the parameter θ_2 of the exponential potential and the parameter θ_3 of the modified exponential potential are arbitrarily fixed. This restriction will then be relaxed by utilizing profile pseudo-likelihood for different test values of these "irregular" parameters, to find global maxima of the pseudo-likelihoods of the proposed models. To implement maximum pseudo-likelihood, the program Spatstat (Baddeley and Turner 2005) will be utilized to the degree possible, with the toroidal correction used to handle edge effects (Ripley 1988).

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**Measuring
Complexity II**

Thoughts on the Development of New, Appropriate Measures of Complexity

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Introduction

Mixed-use managed forests are becoming more complex. The simple agronomic model of single cohort monocultures is expensive to maintain in most situations and is also becoming socially unacceptable in many situations. Around the world there is increased use of mixed species, irregular age structures, and irregular spacings. Concerns about water quality, fish populations and wildlife habitats have led to density and tree species regulations in riparian zones. Concerns about aesthetics have led to irregular edges on cut blocks. Most importantly, concerns about wildlife, biodiversity, and aesthetics have led to partial retention of green trees in areas being harvested and regenerated. Of course, there has also been a demand for more use of various uneven age structures applied more uniformly in the forest.

As a result, forest management has undergone a paradigm change. Stand complexity is not only being maintained, but even created. The old paradigm, the agronomy based model, had distinct forest stand boundaries and simple, uniform stand characteristics (like an agricultural crop). We became interested first in how to put complex stands into our framework of stand measures designed for simple stands. Then, when complexity itself became an indirect goal, we tried to develop measures of complexity to measure how different our stands were from the simple stands. We then justified these measures by showing how relevant they might be to some of our primary objectives, such as wildlife habitat.

Discussion

To move to a new paradigm of forest management some of our basic assumptions for measurement of forest complexity may have to be abandoned. We will explore three such assumptions that must be questioned to demonstrate the degree to which our thinking must change.

1. Boundaries for measurement areas are unique and static

The very concept of the stand must be drawn into question. According to silvicultural textbooks the stand

is defined as a contiguous group of trees sufficiently uniform in species composition, arrangement of age classes, site quality, and condition to be a distinguishable unit. Often we have modified this biological definition to include a constraint of minimum size such that it can be managed as a single unit. The biological definition must be retained so that our knowledge of stand dynamics can continue to guide management, but our measures of complexity must not be so limited.

An important issue is what is "sufficiently uniform"? In the agronomy model of forestry a stand was similar to an agricultural crop and the goal was to make it as uniform as possible. Every effort was made to optimize site conditions through site preparation, optimize genetics through planting select stock, and optimize stocking and spacing by planting and thinning. If the stand was not uniform it was generally not considered to be growing timber optimally. As we move into real management for multiple goals (not single objective with constraints), we must include in our measurement the fact that each objective needs to be considered on a different scale. Our areas of concern (boundaries) need to be simultaneously at different scales.

2. There is a unique and "correct" measure of complexity

Too often we look for the "right" answer, which implies a single answer. This concept is also rooted in our management ideas of optimization. We have to move to a broader concept of multiple answers. Just as we move to acceptance of complexity of stand and forest structures we must move to acceptance of a complexity of forest and stand measures. Just as we consider different objectives we must include different measures of complexity. Our decision tools must include these different measures for each objective.

3. Variation between spatially unique sample points should be averaged

The paradigm shift has major implications for the basic data that are used for management planning. In the old paradigm data from all inventory plots in a stand were averaged to determine a stand average

and the associated standard deviation. This approach was based on the concept that a stand was sufficiently uniform that it could be managed as a uniform unit. Under the new paradigm all information about variation that is unique to a specific location of a plot must be retained.

Stand averaging of inventory data was logical under the old paradigm because it fit the goal of reducing variation, but has had significant impacts on most of the quantitative tools we use in forest management. Averaged data used much less data storage space and also made forest level calculations much simpler. Most of our techniques involve applying stand averaged data to a map polygons or using polygon (stand) size to compute per unit area statistics to be applied to the entire forest operating area. We have assumed that this concept could then be expanded to complex stands. This assumption has directed our development and use of complexity measures. Each measurement point is unique.

Examples of New Approaches

Preserving the uniqueness of information has always been very important when describing topography. Let us consider just three measures of topography that are important information for managers: elevation, steepness, and aspect. The combination of these three measures describes the complexity of the land surface. Also various combinations of these measures can be used to generate other useful descriptions such as roughness. These three measures can be considered analogous to some of the measures we are interested in such as volume, species composition, and age.

Geographers first start with basic measures from known places, such as elevation at a triangulated or "GPSed" location. This is basically what we do with sample or inventory plots. However, the main difference is that they maintain the exact location as an integral part of the information. Information between sample points is then filled in with mathematical algorithms. This creation of information can be as simple as straight interpolation assuming a linear change between known points. Very early on geographers learned that it is possible to include additional insight into the nature of the change between sample points and apply this knowledge to more closely approximate the actual change.

This added information could be as simple as artful correction of topographic maps by examining stereo-pairs of aerial photos. As time progressed more detailed mathematical algorithms were developed to replace the "art" or aerial photo interpretation.

This building of topographic maps is in contradiction to our common three assumptions. The areas of study do not have unique and static boundaries. It is possible to consider topographic complexity on any scale, and the scale will change according to purpose. As well as having a variable scale, the measures of topographic complexity vary according to purpose. Steepness, a measure of change of elevation per linear measure, which is related to both hiking difficulty and skidder operability is expressed differently in both cases. Also steepness is not the same as deflection which is important for cable logging effectiveness.

The development of new and exciting algorithms is now the basis of LIDAR research. Impulse return times are interpreted in many different ways for many different reasons. Again, the scale of interpretation is not set and interpretation is dependent many times on complex methods of interpolating between specific data points.

Conclusions

We must be willing to question many of our basic assumptions in forestry and plant biology in our efforts to measure complexity in a manner directly usable in our management decisions. This may mean having multiple scales, areas, and measures simultaneously developed for different objectives. Just as we became interested in complex stands when we embraced the idea that there was not a single type of optimal stand structure, we must embrace the idea that for the same reasons there is not a single optimal structure to the type of measures that must be developed.

We must let our reasons for knowing the degree of complexity drive our development of measures of complexity. It is important to keep as our focus the reasons for having complex stands just as optimal timber production drove our development of simple stand measures.

Diversity Indices in Forest Inventories, Based on Angle Count Sampling

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Introduction

Sampling for diversity indices is usually discussed on the stand level, i.e. sampling designs are tested for their reliability and accuracy for describing the species or structural diversity of individual stands. Strategic forest management inventories usually do not have a sample grid that allows for the description of individual stands, but rather for strata like age classes, forest types, a.s.o. The objective of this presentation is therefore to (i) demonstrate how diversity measures are assessed in the course of a strategic management inventory based on angle count sampling, and (ii) to discuss the significance of the thus derived diversity measures.

Materials and Methods

In the investigated forest management district of 750 hectare, clear cutting has been abandoned 40 years ago and gradually replaced by target diameter harvesting (Reininger 1987). This is well reflected by the age class distribution. In the majority of stands the upper layer is already older than 120 years.

Two hundred forty five plot centres were established in a square grid. On each of the plot centers sample trees were selected by an angle count with a basal area factor $BAF=4m^2ha^{-1}$ with Bitterlich's (1984) mirror relascope. Each tree within this sample was assessed for species and dbh (given to the nearest cm). The plots themselves were described for the age class of the dominant layer, a stand development stage (younger than 100 years, if older than 100 years having established or not yet established regeneration, or being already a two or more layered stand), a forest mixture type, a regeneration type according to the mixture of the regeneration and a regeneration development class according to the height and coverage of the natural regeneration. In order to calculate spatially explicit diversity indices, from each sample tree its nearest neighbour was determined, irrespective if it fell into the angle count or not. Thus each tree of the angle count was regarded as possibly being a tree on the edge of the plot and treated accordingly (Pommerening and Stoyan 2006). The distance to this nearest neighbour was measured, its species was assessed and its dbh measured.

From these data the following figures and indices were calculated:

The stem number per hectare with $n_{rep}/ha=BAF/(dbh^2 \cdot \pi/4)$ and the basal area per hectare as $ba_{rep}/ha=BAF$ by species. From the proportions by species, the Shannon-index (Shannon and Weaver, 1949) was calculated as $ShannBA$ or $ShannN = -\sum p_i \cdot \ln(p_i)$ with p_i the proportion of the i^{th} species, by basal area ($ShannBA$) and by stem number ($ShannN$). As a spatially inexplicit index of the forest structure the Gini-index (Gini 1921) was calculated from the area under the Lorenz-curve, which in turn was derived when the cumulative basal area proportions of the trees/ha were plotted against the cumulative proportions of the stem number per hectare. The coefficient of variation and the skewness of the dbh-distribution were additionally calculated as spatially inexplicit structural diversity measures.

As a spatially explicit species diversity measure, Pielou's Index of Segregation (Pielou 1961) was determined for spruce (*Picea abies* L. Karst.), fir (*Abies alba* L.) and beech (*Fagus silvatica* L.). As spatially explicit structural indices the Clark-Evans index (Clark and Evans 1954) and a differentiation index, similar to Fuldner (1995) were calculated.

Note that for all indices, the respective calculations had to be weighted by the represented stem numbers per hectare, n_{rep}/ha .

Results and Discussion

The over all distribution of the indices (Table 1) shows that the Shannon-index ranges from zero (only one species) to about 1.4, which is equivalent to 4 uniformly distributed species. The respective quartiles show that 50 % of the plots have a Shannon-index equivalent to 1.5 to 2.5 uniformly distributed species. The Pielou-indices of all three investigated species is represented nearly by its full range (-1 to +1), although 50% of the plots have a nearly independent spatial distribution. The spatially inexplicit structural indices exhibit a large variation from nearly no structural diversity (e.g. coefficient of variation of the dbh distribution, $c\%$ only 2.1% to approx. 120%). The skewness indicates dbh-distributions which are moderately right skewed to heavily left skewed, the latter ones being typical for uneven-aged forests. The majority of the plots (75%) exhibit random to regular spatial distribution of the trees, while only few plots exhibit a typically clustered distribution (Clark-Evans $<< 1$).

Table 1. The overall distribution of the diversity measures (*n* is number of plots).

	Spatial/ nonspatial	Index	Minimum	Lower quartile	Median	Upper quartile	Maximum	n
Species diversity	In- explicit	ShannBA	0.000	0.420	0.637	0.897	1.468	218
		ShannN	0.000	0.377	0.631	0.828	1.459	218
	Explicit	Pielou spruce	-0.870	-0.128	0.000	0.057	1.000	175
		Pielou fir	-0.638	0.000	0.000	0.000	1.000	71
		Pielou beech	-0.702	-0.110	0.000	0.171	1.000	149
Structural diversity	In- explicit	c%	2.1	18.4	23.6	35.9	119.2	218
		skew	-0.942	0.223	0.608	0.994	4.172	216
		Gini	1.800	17.250	23.100	33.150	74.400	218
	Explicit	Clark -Evans	0.208	0.983	1.408	1.996	3.366	217
		Differentiation	0.065	0.236	0.343	0.445	0.844	218

The correlations (Table 2) show that the two Shannon-indices are so highly correlated, that calculating only one of these is sufficient, because there is no additional information gained from the other. The same is true for the coefficient of variation and the Gini-index (Table 3). For the other indices it is essential that they do not correlate sufficiently to be replaced by each another, although in some cases significant correlations exist (Tables 2 and 3).

Most of the indices differ by one or the other stand classification (Table 4), although the respective variance explanations indicate that the classification in no case can be replaced by the indices.

Conclusions

The spatial indices of species and structural diversity investigated in this inventory are meaningful, because they (i) describe the species composition and the structure of the forest district in the expected way, (ii) differ between classes of stands which have been assessed by ocular inspection, and (iii) although

significantly correlated with respective non-spatial indices provide additional information.

When the nearest neighbours of the sample trees in angle counts are assessed irrespective of being part of the sample or not, the spatially explicit indices can be derived in angle count based inventories with only little additional field work.

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Table 2. Correlations between species diversity measures (** means significant at $p < 0.001$, * at $p < 0.01$, * at $p < 0.05$, and n.s. is not significant)

	Shannon BA	Shannon N	Pielou spruce	Pielou fir	Pielou beech
Shannon BA	1.000	0.926 ***	0.441 ***	0.475 ***	0.531 ***
Shannon N		1.000	0.436 ***	0.432 ***	0.489 ***
Pielou spruce			1.000	0.009 n.s.	0.238 **
Pielou fir				1.000	0.072 n.s.

Table 3. Correlations between structural diversity measures (significance see above).

	c%	Gini	skewness	Clark- Evans	Differentiation
c%	1.000	0.960 ***	0.539 ***	0.190 **	-0.042 n.s.
Gini -index		1.000	0.307 ***	0.307 ***	-0.050 n.s.
Skewness			1.000	0.130 n.s.	-0.089 n.s.
Clark -Evans				1.000	-0.487 ***

Table 4. Variance explanation (R^2) of the indices by the stand classifications assessed in the inventory. (**Bold and italic** is significant with $p < 0.01$, **bold** with $p < 0.05$, and *italic* with $p < 0.10$)

	Shannon		Pielou			c%	Gini	Skew	Diff.	Clark Evans
	BA	N	spruce	fir	beech					
Stand developm. class	0.13	0.11	0.04	0.09	0.03	0.08	0.10	0.02	0.09	0.04
Stand mixture type	0.32	0.29	0.08	0.13	0.05	0.03	0.04	0.03	0.05	0.04
Regen. developm. class	0.01	0.04	0.02	0.11	0.01	0.16	0.17	0.07	0.01	0.04
Regeneration mixt. type	0.06	0.06	0.01	0.10	0.01	0.13	0.15	0.07	0.02	0.01
Browsing	0.03	0.04	0.00	0.05	0.00	0.03	0.04	0.03	0.03	0.01

Sensitivity of Diversity Indices to Management Effects in Forest Stands

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Introduction

A large number of indices to describe species and structural diversity within forest stands have been developed. A number of investigations deal with their assessment and accuracy when sampled. Sterba and Zingg (2006) tested 13 indices with a relevancy to structure and diversity and compared them.

However, there is a need to investigate the accuracy and the sensitivity of their change, as caused by forest management measures, intended to change the structure of stands towards a higher or lower complexity level.

Material and Methods

The data of the study comprise permanent sample plots in stands which were treated in order to (i) convert them from an even-aged structure towards an uneven-aged one, (ii) keep their uneven-aged structure at equilibrium, (iii) structure even-aged stands through different thinning methods. We selected 13 permanent plots from Austria and Switzerland which were to be converted or which have had a constant structure and diversity for a long time. The observed time ranges from 10 to 100 years with 4 to 17 surveys. Spatially explicit data are available on these plots from only 4 to 5 surveys.

As a basis of comparison for all these stands, an equilibrium model according to Schütz (2006) was calculated. The deviation of the real diameter

distribution from the one of the equilibrium model is expressed as the variance of the logarithmic diameter distribution around the equilibrium distribution VAR (Zingg and Duc 1998). On this basis the plots were assigned to a scenario. For this summary we selected three examples which are representative for the scenarios mentioned above:

Spatially explicit as well as spatially inexplicit indices have been investigated. In a first step all the indices for all plots and correlation matrix for all the indices were calculated. From there the indices for further investigations were selected. To describe structure, we selected the coefficient of variation C_{DBH} (%), the skewness of the dbh-distribution (SKEW) and the Gini-Coefficient (Gini) as well as the index of Clark and Evans to describe the horizontal distribution of the trees. To assess changes in species diversity we used the Shannon-Weaver index as well as the Simpson index, both taking into account the number of trees (N) and the basal area (G). To describe the intermingling of the species, we used Pielou's index and the intermingling index of Földner (literature concerning indices cited in Sterba and Zingg 2006).

Results

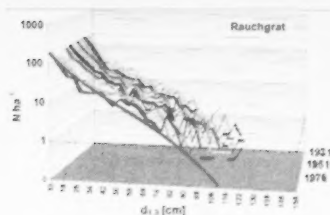
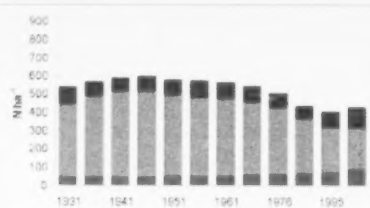
The index VAR (deviation from the equilibrium) is below 0.5 over the whole time, describing a steady state. Also C_{DBH} and the Gini-coefficient show no change over time. Only the SKEW varies more but remains clearly positive. Species diversity (Shannon-

Table 1: Selected plots

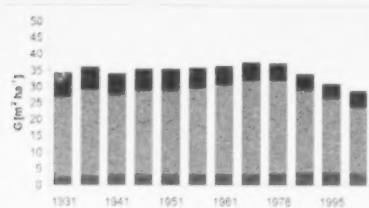
Plot Id	Number of observations	Period of observation	Number of trees (min.- max.)	Scenario
SW -02047 Rauchgrat	12	1931 -2003	1305 - 1650	Equilibrium structure maintained
SW -01034 Gian d'Alva	10	1921 -1999	439 - 652	Tree species loss and the equilibrium structure towards a two layered stand
SW -02034 Buttes	15	1913 -2006	142 - 900	Even-aged stand in conversion to an uneven-aged stand

Example #1: Maintained equilibrium structure

■ Norway spruce □ Larch ■ Beech
 ■ Silver fir □ Stone pine

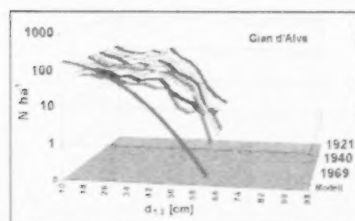
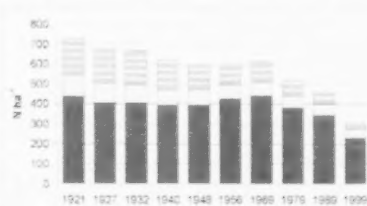
Diameter distribution and equilibrium model (1st row)

Number of trees

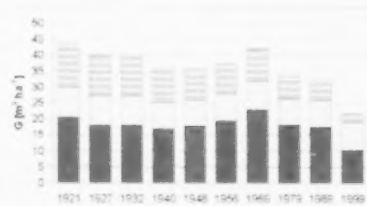


Basal area G

Example #2: Losing the equilibrium structure towards a two layered stand.

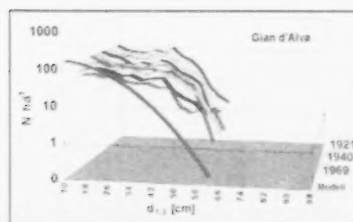
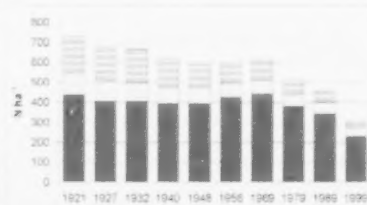
Diameter distribution and equilibrium model (1st row)

Number of trees

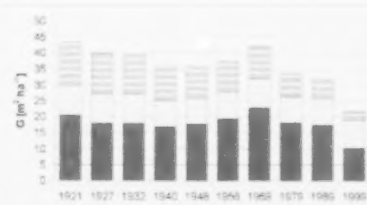


Basal area G

Example #3: Even-aged stand in conversion to uneven-aged.

Diameter distribution and equilibrium model (1st row)

Number of trees



Basal area G

Weaver- and Simpson-Index) of number of trees rose while the same indices for the basal area remained stable over the whole observation period. This reflects the absolute and relative change of species in numbers but not yet in basal area.

This stand was not at an equilibrium stage at the beginning of the observation. Despite regular interventions the situation did not improve. VAR rose from 1.3 to 1.7, i.e. 28 %. C_{DBH} and the Gini-coefficient did not change in a clear way, SKEW rose a little but

was always close to 0 (symmetrical distribution). The number of trees dropped to 69% and the basal area to 83%. Species diversity dropped slightly but these values do not reflect the fact that one species – larch – is no longer represented in the lower diameter classes, i.e. it will disappear if silvicultural measures are not adopted. This situation is only noticeable when checking the changes in the different canopy layers.

VAR is very high (> 3) at the beginning because this stand was even-aged at the first survey. The sudden raise of the C_{DBH} , SKEW and the Gini-coefficient in

1947 is an artifact. In 1947 the new generation of trees was included in the survey. This is only noticeable in the number of trees and not so much in the basal area. The change of the species is clearly shown in the Shannon-Weaver and the Simpson-Indices. In none of the cases discussed here, a clear correlation could be established between the distant-dependent indices and the changes of stand characteristics.

Discussion

The results reveal that C_{DBH} , SKEW and the Gini-coefficient show the differences in the status of a stand as Lexerød and Eid (2006) demonstrated, but they respond to the treatments in the expected way only if the structural changes are strong. We obtained a better result for the indices which show species diversity and their changes. The indices based on the number of trees react earlier than those based on basal area. Including more data will lead to more reliable results.

Conclusion

In forests with protection functions it may be important to maintain complex stand structures through silvicultural measures. Due to the fact that the changes which are important for the long-term development of a stand, occur mainly in the lower canopy and the lower diameter classes, it is important to develop existing indices to detect changes in these classes or to develop new indices with this aim. The index VAR presented here shows general changes of a complex structure but it is not able to detect the real cause which should be known to take the necessary measures.

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A Stand Structural Diversity Index for Horizontal, Vertical, and Spatial Diversity

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Introduction

Stand structure is an important element of stand biodiversity (e.g., Freemark and Merriam 1986), and measures of stand structural diversity are also important for predicting future stand growth and development (Pretzsch 1997). Several indices of stand structure have been proposed based on tree attributes, particularly species and tree size; a few authors have suggested indices that combine a mixture of spatial diversity (arrangement) and tree attribute diversity into an overall structural index (Pommerening 2002). In this paper, we illustrate the use of a possible index for stand structure based on species, size variables, coupled with spatial arrangement (LeMay and Staudhammer 2001 and in prep.). We defined a most heterogeneous (most structurally diverse) stand as a uniform (or even) distribution over species and size variables, and a nonhomogeneous Poisson spatial distribution.

Description of the Stand Structural Index

A stand structural index (STVI) based on species, height, and dbh (diameter outside bark at 1.3 m above ground), labeled STVI, was developed and presented in Staudhammer and LeMay (2001). STVI was based on the variance of basal area per ha for dbh and height relative to the variance for a maximally diverse stand with a uniform distribution of dbh and height, as shown for diameter (STVIdbh, for a species i):

$$STVI_{dbh,i} = \begin{cases} 1 - \left(\frac{S_{dbh,i}^2 - S_{dbh,i}^2}{S_{dbh,i}^2} \right)^{p1}, & \text{when } S_{dbh,i}^2 \leq S_{dbh,i}^2 \\ 1 - \left(\frac{S_{dbh,i}^2 - S_{dbh,i}^2}{m \times S_{dbh,max}^2 - S_{dbh,i}^2} \right)^{p2}, & \text{when } S_{dbh,i}^2 > S_{dbh,i}^2 \end{cases}$$

where $S_{dbh,i}^2$ is the variance of dbh for species i , calculated by:

$$S_{dbh,i}^2 = \frac{\sum_{j=1}^n [w_j \times (x_j - \bar{x})^2]}{\sum_{j=1}^n w_j}$$

where x_j is dbh, (or height); w_j is the basal area per ha represented by the j th tree in the sample plot; is the

average of dbh or height, weighted by basal area; and n is the number of trees in a sample plot. The variance of a uniform distribution is given by:

$$S_u^2 = \frac{(b - a)^2}{12}$$

where a and b define the range of the distribution, differing for dbh versus height. The maximum possible variance of a distribution occurs when the distribution is maximally bimodal, when half the basal area is at a and half the basal area is at b , with a variance of:

$$S_{max}^2 = \left[\frac{1}{2} \times \left(\frac{a+b}{2} - a \right)^2 + \frac{1}{2} \times \left(b - \frac{a+b}{2} \right)^2 \right] = \frac{(b-a)^2}{4}$$

The values for $p1$, $p2$, and m were obtained by constraining the index to: 1) 0.5 for a uniform distribution over half the maximum possible range; 2) 0.5 for a bimodal distribution, with half of the values uniformly distributed over the lower quartile, and the other half uniformly distributed over the upper quartile of the maximum possible range; and 3) 0.1 for a maximally bimodal stand. Using these constraints, $p1=2.4094$, $p2=0.5993$, and $m=1.1281$ (see Appendix of Staudhammer and LeMay (2001) for details).

A separate component spatial distance was then developed (LeMay and Staudhammer in prep.). A nonhomogeneous Poisson spatial distribution, based on a number of different sized clumps of trees, was considered the most diverse spatial arrangement; this might result from microsite variability, inter-tree competition over different species and tree sizes, and/or local disturbance events. We used the variance of all possible distances between trees. The index was then defined as:

$$STVI_{dist} = \begin{cases} 1 - \left(\frac{S_{dist}^2 - S_{dist}^2}{S_{dist}^2} \right)^{p1}, & \text{when } S_{dist}^2 \leq S_{dist}^2 \\ 1 - \left(\frac{S_{dist}^2 - S_{dist}^2}{m \times S_{dist,max}^2 - S_{dist}^2} \right)^{p2}, & \text{when } S_{dist}^2 > S_{dist}^2 \end{cases}$$

where S_{dist}^2 is the target stand variance of distances for all species; $S_{dist,max}^2$ is the variance for a most spatially diverse stand; $S_{dist,max}^2$ is the variance of a

distribution of two maximally separated equal-sized clumps, with Poisson spacing within clumps. The constants p_1 , p_2 , and m were obtained by constraining the index to: 1) 0.2, for a Poisson distribution, where the number of clumps is less than or equal to the number of trees; 2) 0.5 for a diverse stand with a Poisson distribution of different sized clumps, but half the diversity of maximal diversity; and 3) 0.3 for maximally separated equal-sized clumps. Since expected values for the variances of each spatial distribution are not known, Monte Carlo simulations would be needed to obtain these variances as with other spatial indices (Dale 1999).

Illustration on the Use of the Stand Structural Index

To illustrate how the calculated STVI might be used in developing allometric equations, we calculated STVI for eight stem-mapped permanent sample plots (PSPs), varying in size from 0.04 to 0.10 ha (Table 1).

Functions to predict height as a function of dbh were then fitted. Plot level variables from Table 1 were then added to the equations (Table 2).

The use of plot level variables, resulted in improvements to the height prediction function, although adding the more simply calculated basal

area per ha and stems per ha gave results similar to including the stand structural indices. In applying this to crown length models (not shown), a similar result occurred, except that the stand structural indices resulted in some increase in precision over the addition of basal area and stems per ha.

Conclusions

STVI was developed as a stand-level structural index that can be decomposed into diversity of dbh, height, and spatial arrangement by species. Stand structural indices can be used for comparison of stand diversity, and in modelling growth and yield of stands. However, any use of these indices should be tested, as other stand variables that are more simple to calculate may provide similar results.

Acknowledgements

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Table 1. Structure diversity indices, stems per ha, basal area per ha, and species richness for eight PSPs.

Plot	STVI dbh	STVI ht	STVI d+h	STVI dist	Stems per ha	Basal area per ha	Species Richness
1	0.215	0.135	0.175	0.145	385.32	11.16	3
2	0.118	0.111	0.114	0.137	760.76	17.58	2
3	0.863	0.590	0.726	0.145	843.11	30.50	9
4	1.250	0.710	0.980	0.156	1525.00	28.65	5
5	0.023	0.043	0.033	0.173	1125.00	8.93	2
6	0.315	0.355	0.335	0.172	3050.00	53.37	4
7	0.833	0.894	0.864	0.144	1860.00	39.28	3
8	0.268	0.249	0.259	0.226	1100.22	13.08	8

Table 2. Coefficient of determination (R square) for the base model ($\text{height} = f(\text{dbh}, \text{ln dbh})$) versus models with plot level variables.

Species	No. of Trees	R square						No. of Plots
		dbh, ln dbh	+ Richness	+ STVI dbh STVI dist	+ba/ha, stems/ha	+ba/ha, stems/ha, STVI d	+ba/ha, Stems/ha, Richness	
Western red cedar	41	0.85	0.91	0.95	0.95	n/a	n/a	3
Douglas fir	127	0.85	0.85	0.93	0.94	0.95	0.95	7
Hemlock	36	0.89	0.91	0.93	0.93	n/a	n/a	3
Larch	116	0.88	0.88	0.97	0.96	0.97	0.97	4
Pine	54	0.40	0.41	0.59	0.91	0.92	0.92	5
Spruce	149	0.80	0.94	0.94	0.92	0.94	0.94	4

A Quantitative Technique for Stand Structure Classification

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Introduction

Stand structures have traditionally been classified with consideration for the effects of disturbance (e.g. stand initiation), competition (e.g. stem exclusion), average size of trees (e.g. sapling versus pole), species composition, seral stage (e.g. young versus old), spatial arrangements (e.g. open versus closed) and vertical structure (e.g. single versus multi-layered trees; Oliver and Larson, 1990; O'Hara et. al. 1996; O'Neil et. al. 2001). Such qualitative terms are then matched with more quantitative descriptors (e.g. quadratic mean diameter, percent cover) to assist users in applying the classification. These classifications have only a loose fit with the objects being classified, such that two classifiers may justifiably assign two different classes to the same stand structure type. The purpose of this research was to develop a truly quantitative system of classification that would be generally applicable and that could be applied consistently (i.e. a single observer would assign the same class to the same object on multiple occasions), reliably (i.e. two observers would assign the same class to the same object, and if not there would be a definitive way to determine the correct class), concisely (i.e. simple labels could be applied to the classes), without subjectivity (i.e. labels would not imply anything more than the objects that they refer to and they do not infer processes or values that are not intrinsic to the objects being classified), and with precision (i.e. within class differences are minimized and between class differences, maximized).

Methods

Four hundred and twenty-two plots, both fixed area ($1/10^{\text{th}}$ hectare) and combined fixed and variable radius, were established in a wide variety of stand structures in the central interior region of British Columbia. All trees above breast height (1.3 m) were measured on each plot. Only living trees were used to build the classification. The data were compiled in 3 steps to produce a 17-class system for representing the variety of stand structures as follows:

- Construct a distance matrix
- Determine a suitable number of stand structure classes
- Search for the best arrangement of plots amongst the classes

Constructing a distance matrix: Two cumulative distributions were compiled for each plot representing

(1) the numbers of trees per hectare and (2) basal area per hectare, greater than or equal to a given diameter threshold, starting with the largest tree diameter (140 cm) and working toward 0 cm in decrements of 1 cm. Differences relating to tree species were ignored, but the methods described herein were subsequently extended to deal simultaneously with tree species and size differences amongst plots. The next steps in the process are described with reference to the numbers of trees per hectare, but apply equally well to basal area per hectare. For each plot the total number of trees per hectare greater than or equal the 0 cm dbh threshold were ranked from smallest to largest. The lowest number of trees per hectare was set equal to 0 and assigned a rank of 0. The rank was converted to a proportion between 0 and 1 by dividing each plot rank by the highest rank in the set. The plot cumulative distributions representing the numbers of trees per hectare were each normalized by interpolating the proportion relative to the actual numbers of trees per hectare associated with each diameter threshold. Each plot was then compared with every other plot by summing the absolute differences in the normalized, cumulative numbers of trees per hectare at each diameter threshold (intervals of 1 cm) and entering the resultant value into a table. Finally, for each plot pair, the resultant values (differences), one representing normalized numbers of trees per hectare and the other basal area per hectare, were squared and summed before taking the square root. Thus a final, single figure was derived to represent the degree of difference, or distance amongst each pair of plots.

Determining a suitable number of classes: It was decided that 17 would constitute a reasonable number of stand structure classes. The goal was to avoid having too many classes such that the classification would be unwieldy for use in the field and would also be unreliable without putting in plots. The goal was also to avoid having too few classes such that there would be little gained in terms of the precision with which each class represented one set of structural conditions and not others.

Search for the best arrangement of plots amongst the classes: The following is an abbreviated description of the cluster algorithm used to derive the final system of stand structure classification. Each plot was randomly assigned to 1 of 17 classes, subject to the constraint that no class could have less than 2 members assigned to it at any time. The algorithm then evaluated each

plot in terms of its potential for movement to one of the remaining 16 classes. For each move the change in "between class distances" was equal to the sum of the distances between the plot being evaluated and the remaining plots in the group to which it was initially assigned. The change in within class distances was equal to the sum of the distances to each of the plots in the group to which it was tentatively being assigned. A plot was finally selected for movement to a new group if the ratio of the change in within group difference to the change in between group difference was a minimum relative to all other potential plot-group movement combinations. This process was applied repeatedly until there was no ratio less than 1. This stopping rule was later modified, such that the program stopped at a point when the same observation repeatedly oscillated between two different groups.

Results

The algorithm demonstrated steady progress in the reduction of within class differences and increase in between class differences. Based on logic alone, it could be observed that each new member added to a class resulted in an increase in the sum of the differences relative to the remaining members, such that as the number of observations in a given class increased, assignments to the remaining classes become more favourable. In portions of the domain where there had been intense sampling, the result was that the numbers of observations assigned to a given class tended to increase, but the domain represented by that same class tended to decrease, leaving a larger domain to be covered by the remainder of the classes. The result was that intensively sampled domains tended to have slightly more observations that covered a relatively narrow range of conditions, while poorly sampled domains had fewer observations and represented a broader range of conditions relative to the average.

A compiler was built to classify new plot or stand conditions. When the original plots (used to build the classification in the first place) were classified using the compiler, only 1 out of 422 was misclassified.

Discussion

Cumulative distributions were used instead of diameter classes as the basis for comparison to ensure that the classification would be independent of any diameter class boundary definitions. Both basal area per hectare and the numbers of trees per hectare were used to give equal weight to large and small trees alike. Normalization helped to ensure that both of these variables were given equal weight. Rank normalization changed the relative degree of spread amongst the plots, such that in those parts of the entire domain

where sampling was intense, the plots would be more spread out than they might otherwise be. Conversely, in those parts of the domain where sampling was sparse, the plots would be more nearly similar than they might otherwise be. This contributed toward the goal of ensuring that groups were not formed based on representation by a single, or even a small number of samples. Lastly, non-parametric distributions were used to ensure that classification had a strong empirical foundation that was not biased or conditioned in the first instance by the reduction of data down to a set of parameters.

The last step in the process involved development of an alternative cluster algorithm. K-means clustering was not used, in part because the basic algorithm creates path dependencies. This is as a result of starting with the irrevocable selection of pairs of plots that are most nearly similar and joining them to form a group. This approach had been tried in attempts leading up to the final solution described herein, with the result that there were no natural clusters to be found – the dendrogram represented a continuum whereby each plot was added to a single group one at a time until the final group was produced. K-means clustering often results in subdividing datasets such that a few groups represent most of observations while many groups are populated by only 1 observation. The dendrogram illustrated an extreme example of this phenomenon. This is of no use since most of the classes represent unusual conditions and therefore are deployed infrequently. So too there are a much smaller number of classes that are used to represent the majority of cases, and thereby resulting in inadequate separation where differences might be recognizable and important. In the cluster algorithm developed for this study, more control could have been obtained over where the splits between the groups occurred by applying different weights to each of the groups at the end of the process, and then using this as basic input, instead of using an initial, random assignment of plots to each group.

Conclusion

Methods were developed to build the system of stand structure classification that involved subdividing a broad continuum with no natural subdivisions. They used non-parametric techniques and methods that accounted for a trade-off between the numbers of observations in each group versus the size of the domain thereby represented. The result was a classification that was more generally applicable to the description of a wide range of conditions, subject to the limitations in the kinds of samples available to represent such a range. The final classification was demonstrated to be reliable, and reasonably precise given the desire to produce a system involving 17-classes.

A Percent Stocking Index for Boreal Mixed-Species Stands in Alberta

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Introduction

Percent stocking was used in this study as a measure of spatial tree dispersion derived from fixed-area permanent sample plots. It was defined as the percentage of 10 m² subplots occupied by at least one tree ≥ 1.3 m in height. The objective was to develop percent stocking models that could be used to improve growth and yield forecasts for 4 major tree species growing in boreal mixed-species stands: aspen (*Populus tremuloides*), white spruce (*Picea glauca*), lodgepole pine (*Pinus contorta*) and black spruce (*Picea mariana*). Corresponding species codes are: Aw, Sw, Pl and Sb.

Materials and Methods

Percent Stocking (PS) Calculation

Stem mapped permanent sample plots (typically 31.62 m by 31.62 m) were used. Each plot was divided by a square grid into 10 m² cells, starting from the southwest corner. This resulted in 3 types of cells for plots that did not fit the grid exactly: full cells, partial side cells on the right and at the top, and a corner cell (northeast corner). Plot sizes that accommodated the grid exactly had only full cells. Each cell was classified as either stocked or non-stocked for each species present. If a cell was occupied by at least one tree of a species, it was recorded as stocked with that species. Otherwise, it was non-stocked. Stocking by species was calculated using the formula below. Area weighting was done to correct edge bias:

$$[1] \quad PS = \frac{n_f + [N_s - (N_s - n_s) \times (A_s / A_f)] + [N_c - (N_c - n_c) \times (A_c / A_f)]}{N_f + N_s + N_c} \times 100$$

where N_f , N_s , N_c = total numbers of full, partial side and corner cells; n_f , n_s , n_c = total numbers of stocked full, partial side and corner cells; and A_f , A_s , A_c = areas of each full, partial side and corner cell. For plots with full cells only, eq. [1] was reduced to: $PS = (n_f / N_f) \times 100$

Model Development and Evaluation

There were two data sets for each species, one for model fitting and the other for validation, except for black spruce where only model fitting data set was available. Using all possible combinations of growth intervals (Wang et al. 2004), stocking data were arranged into pairs of (PS_1 , AGE_1) and (PS_2 , AGE_2), where PS_1 and PS_2 are percent stocking at total ages 1 and 2, respectively. A difference equation technique was used for model fitting based on a constrained logistic model form. Site index (SI) was found to be a significant predictor and incorporated into the models. Species interactions were evaluated by including stocking percentages of other species as predictors. Analysis revealed that stocking dynamics of aspen and black spruce were not influenced by other species, white spruce stocking was affected by aspen, and lodgepole pine stocking was affected by 3 other species. For aspen, the stocking model took the following form:

$$[2] \quad PS_2 = PS_1 \times \frac{1 + \exp[b_1 + b_2 \ln(AGE_1 + 1) + b_3 \ln(SI)]}{1 + \exp[b_1 + b_2 \ln(AGE_2 + 1) + b_3 \ln(SI)]}$$

A percent stocking index (PSI), similar in concept to site index in top height-site index models, was introduced by replacing AGE_1 with an index age of 50 years. The percent stocking (PS_1) that corresponds to the index age was defined as the PSI. By replacing (PS_2 , AGE_2) with a more generic pair (PS , AGE), the final stocking model for aspen became:

$$[3] \quad PS_{as} = PSI_{as} \times \frac{1 + \exp[b_1 + b_2 \ln(50 + 1) + b_3 \ln(SI_{as})]}{1 + \exp[b_1 + b_2 \ln(AGE_{as} + 1) + b_3 \ln(SI_{as})]}$$

Following the same procedure, stocking models were derived for the other 3 species. Note that PSI was used to represent the impact of a species on the stocking dynamics of another species:

$$[4] \quad PSI_{sw} = PSI_{sw} \times \frac{1 + \exp[b_1 + b_2 \ln(50 + 1)^2 + b_3 \ln(SI_{sw})]}{1 + \exp[b_1 + b_2 \ln(AGE_{sw} + 1)^2 + b_3 \ln(SI_{sw})]}$$

$$[5] \quad PSI_{sw} = PSI_{sw} \times \frac{1 + \exp[b_1 + b_2 \ln(50 + 1)^2 + b_3 \ln(SI_{sw}) + PSI_{sw} / b_5 / 50]}{1 + \exp[b_1 + b_2 \ln(AGE_{sw} + 1)^2 + b_3 \ln(SI_{sw}) + PSI_{sw} / b_5 / 50]}$$

$$[6] \quad PSI_{pi} = PSI_{pi} \times \frac{1 + \exp[b_1 + b_2 \ln(50 + 1)^2 + b_3 \ln(SI_{pi}) + b_4 PSI_{sw} + b_5 \sqrt{PSI_{sw}} + b_6 \sqrt{PSI_{sw}}]}{1 + \exp[b_1 + b_2 \ln(AGE_{pi} + 1)^2 + b_3 \ln(SI_{pi}) + b_4 PSI_{sw} + b_5 \sqrt{PSI_{sw}} + b_6 \sqrt{PSI_{sw}}]}$$

Those models were evaluated graphically and statistically. Graphical inspection was performed on model fitting and validation data (except for black spruce), while statistical evaluation was done on validation data only. Both were conducted for forward and backward projections. Forward projection uses the first measurement of a plot to calculate PSI and predicts stocking values at later measurements. Backward projection uses the last measurement of a plot to compute PSI and predicts earlier stockings. With the graphical approach, predicted stocking and error trajectories were generated for each species. Statistics calculated to quantitatively examine the magnitude and distribution of prediction errors and to determine the accuracy of model predictions included: mean prediction error ($\bar{e} = \sum_{i=1}^k (PS_i - PPS_i) / k$), percent prediction error ($\bar{e}\% = 100 \times \bar{e} / PS$), standard deviation of prediction errors ($SD = [\sum_{i=1}^k (e_i - \bar{e})^2 / (k - 1)]^{1/2}$) and root mean squared error of prediction ($RMSEP = [\sum_{i=1}^k (PS_i - PPS_i)^2 / k]^{1/2}$); where PS_i and PPS_i are the i^{th} observed and predicted stockings ($i = 1, 2, \dots, k$), and PS is the mean observed stocking (Marshall and LeMay 1990).

Results and Discussion

Table 1 shows the estimated coefficients and associated model fitting statistics based on model fitting data. All parameters were highly significant. High R^2 and low RMSE values suggested good fits. Residual plots (not shown) indicated no obvious over- and/or under-estimation. Site index was a significant predictor in all models. Stocking declines faster over time on more productive sites than that on less productive sites, and the decline starts earlier, especially at higher initial stocking levels. These results are consistent with the commonly accepted self-thinning concept (Reineke 1933). Stocking percentages of aspen and black spruce were not affected by other species. White spruce stocking was reduced by the presence of aspen, especially at higher PSI_{sw} values. All 3 species had significant negative impacts on lodgepole pine stocking, with the impact from aspen being the largest, followed by white spruce and black spruce.

Table 1. Estimated parameters and associated model fitting statistics.

Species	N	b_1	b_2	b_3	b_4	b_5	b_6	RMSE	R^2
Aw	732	-12.8453	0.4081	1.2855				3.28	0.97
Sb	428	-17.5947	0.3514	3.3031				3.87	0.98
Sw	1090	-22.7856	0.3872	4.4888				3.41	0.97
Pi	1344	-12.2339	0.2489	2.1000	0.0251	0.0662	0.1141	3.41	0.98

N: number of observations; RMSE: root mean squared error; R^2 : coefficient of determination.

Graphical inspection further demonstrated good model performance. For each species, predicted stocking trajectories from both forward and backward projections performed on both data sets captured the data trends well and associated prediction error trajectories showed no obvious over- and/or under-predictions (graphs not shown). Table 2 lists the validation statistics for aspen, white spruce, and lodgepole pine calculated from the model validation data. All errors were fairly small, demonstrating again that the models performed well. Notice that RMSEPs were fairly close to RMSEs (Table 1), a strong indication that the models predicted well (Neter et al. 1996).

Table 2. Validation statistics calculated from model validation data.

Species	k	$\bar{e}$		$\bar{e}\%$		SD		RMSEP	
		F	B	F	B	F	B	F	B
Aw	110	0.810	-0.866	1.971	-2.000	3.761	4.137	3.830	4.209
Sw	123	-0.357	0.282	-1.070	0.807	3.498	3.698	3.502	3.694
Pl	209	0.215	-0.119	0.341	-0.182	3.080	3.473	3.080	3.467

The importance of regeneration stocking to subsequent stand development has long been recognized in Alberta (Bella 1976), but until now the spatial dispersion of trees and species within stands has not been accounted for in operational growth and yield projections. This limitation is a major concern because, while it is expected that observed differences in fire-origin versus managed stand structures will have important implications (Dempster and Huang 2004), projections for post-harvest stands are currently based largely on models developed from non-spatial, fire-origin stand data. The present study demonstrates both a means and the feasibility of predicting stocking by species over time. These results are being integrated with related findings on stand density and basal area development to provide a growth and yield projection system that takes into account spatial dispersion and inter-specific competition over a wide range of sites and species mixtures.

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Stand Structure Attributes of a Partial Harvested Boreal Mixedwood Stand

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Introduction

In northeastern Ontario, the longer fire cycles (>150 years) associated with more humid boreal climates result in the presence of extensive areas of uneven-aged mixedwood, spruce-fir, and black spruce stands in mid- and late-seral stages of succession. Therefore, if we desire to maintain a natural disturbance pattern with large portions of the landscape in mid- and late-seral stages, the primary use of traditional short rotation (<100 years), even-aged silviculture is ecologically inappropriate. Partial harvesting has been proposed as having the potential of achieving a balance between maintaining biodiversity and ecosystem function, and serving human consumptive needs by retaining enough residual trees to maintain key habitat values such as stand structure and coarse woody debris dynamics.

In 1994, a partial harvest trial of a boreal mixedwood stand was initiated east of Cochrane, Ontario, Canada on the Lake Abitibi Model Forest (MacDonald 2000). A forest tent caterpillar (*Malacosoma disstria*) outbreak occurred during 1997, peaked in 1998, and ended in 1999, accelerating the reduction of the overstory aspen through increased mortality in this area. Thus an opportunity was presented to quantify and compare the effects of partial harvested and unharvested stands when a natural disturbance (insect defoliation) was superimposed on the treatments. In order to help determine whether partial harvesting retains stand characteristics similar to a natural stand during canopy break-up, we completed a 11-year re-measurement of the boreal mixedwood partial harvesting trial. A comparison of the stand structure and input of coarse woody debris between partially harvested and unharvested stands during canopy break-up was made.

Methods

The randomized complete block experimental design included three harvesting treatments. Treatments removed 0%, 42%, and 100% of the merchantable overstory basal area (BA), and were randomly assigned to 100m×100 m units within each of four replications. In 1994, all trees greater than or equal to 4.0 m in height were tagged and measured for total height, diameter at 1.3 m above the point of germination, crown

length, crown width, and extent and type of damage. Harvesting took place in the winter of 1994-1995 with a post-harvest measurement immediately after. A 5-year re-measurement was done in 1999 (MacDonald et al. 2004). In 2005, we re-measured the diameter and height of living trees and assessed the extent and type of damage to live and dead trees. New in-growth into the 4-m class was stem mapped.

The following stand structural indices were calculated and compared across treatments for each of the years 1994 (pre-harvest), 1995 (post-harvest), 1999 and 2005: 1) trees were grouped into 2 cm diameter classes and fitted to a combined exponential and power function of the form: $y = ax^b + c$, where y is density of trees in diameter class x , and a , b and c are regression parameters to be estimated; 2) large living and dead stems were divided into three diameter classes: 24.1 cm – 30.0 cm; 30.1 cm – 40.0 cm; ≥40.1 cm; and 3) a Stand Complexity Index (SCI), defined as the sum of the areas of 3-dimensional triangles connecting the tops of 3 neighbouring trees divided by the sum of the areas of 2-dimensional triangles connecting the bases (Zenner and Hibbs 2000). A SCI = 1 indicates a stand that is composed of trees of equal heights.

Results

The diameter distribution between the unharvested and harvested treatments for all years are relatively similar. From 1994 to 1999 the shape is a combined exponential and power function for both treatments, although the maximum height of the function is greater for the unharvested control in all years. In 1994, the diameter distribution shifts in shape to a power function resembling an uneven-aged reverse-J shaped curve with the y-intercept of the partially harvested treatment significantly larger ($p < 0.0001$) than the unharvested control.

Focusing on the density of large living trees, significant differences were detected between harvested and unharvested treatments for the 24.1-30.0 cm and 30.1-40.0 diameter classes for 1995 (post harvest) through 2005 (Figure 1). However, significant differences were not detected for the >40.0 cm class for the same measurement periods. During the period from 1999 to 2005, there was a significant reduction in large stems in

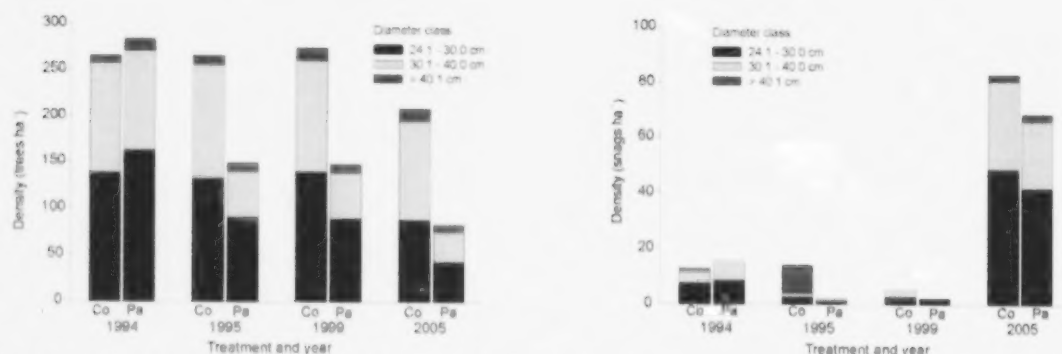


Figure 1. Total number of large living trees (left) and input of large standing dead trees (right) from 1994-2005 for the control (Co) and partially harvest treatment (Pa).

the 24.1-30.0 cm diameter class of both treatments as a result of mortality induced by the forest tent caterpillar infestation. The reduction in the density of large trees is reflected in the increased input of large standing dead trees (snags). The input of snags from 1994-1999 is relatively small for both treatments but there was a significant increase between 1999-2005 for both treatments. The magnitude of the increased input of snags is similar between the treatments.

For the unharvested treatment, the SCI increased with time having a significant positive slope from 1999 to 2005 (Table 1). For the partially harvested treatment, the SCI was more variable without a consistent trend with time and no significant slope. The only significant difference ($P = 0.0104$) between the unharvested and harvested treatments was for the measurement in 2005.

Discussion

The indices used here show that partial harvesting maintains some of the stand structure characteristics of the natural condition but differs in possibly important aspects. There were significant differences in the density of trees in the 24.1-30.0 and 30.1-40.0 diameter classes which are important size classes for important habitat features. Further, although the input of snags was similar between the partially harvest

and unharvested treatments, the difference in living large trees may mean future differences in the input of large snags. The unharvested treatment has at least twice as many large living trees in "reserve" for future snags. The SCI between the partially harvested and unharvested treatments was different 11 years after harvest, and the unharvested SCI was still increasing with time. The unharvested area appears to be gaining in structural complexity as the stand proceeds through the stand break-up period despite an insect-induced acceleration of aspen mortality. It appears that aspen mortality may be random in spatial pattern and among trees of different sizes. The partially harvested area, on the other hand, exhibits further reduction of overstory aspen by the forest tent caterpillar which resulted in a decrease in SCI in 2005.

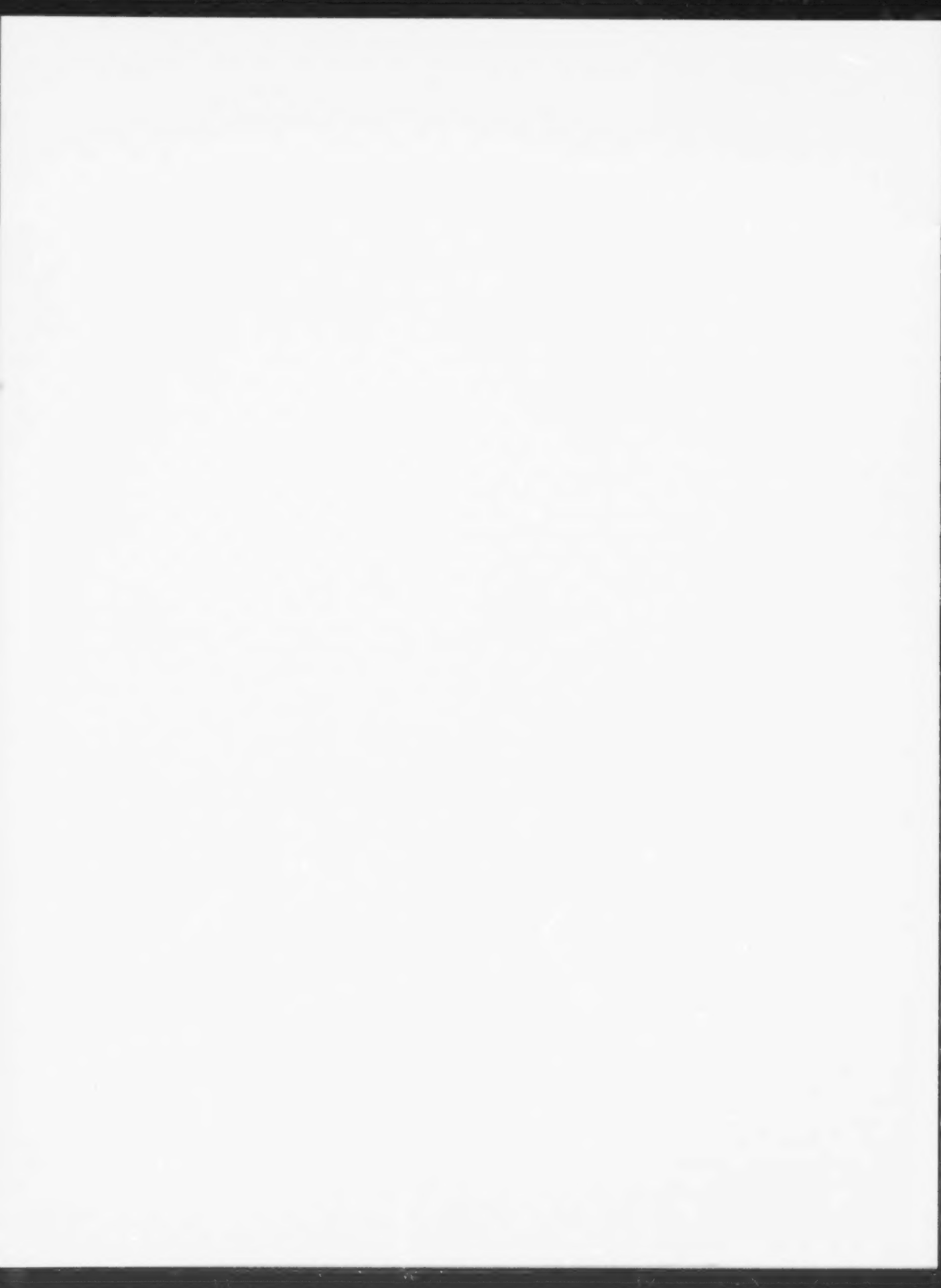
This study illustrates that rather than conceptualizing partial harvesting as an emulation of the natural disturbance pattern, it may be more appropriate to view partial harvesting as a mid-rotation stand entry under extended rotations in areas with long fire cycles. Under this concept, harvesting is viewed as removing a portion of the anticipated mortality which will occur anyway. Whether the stand characteristics maintained with partial harvesting translates into habitat value will require long-term, large-scale research installations.

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Table 1. Mean stand complexity index values (standard error of the mean in brackets) between unharvested and partially harvested treatments for the years 1994 (pre-harvest), 1995 (post-harvest), 1999 and 2005, for the unharvested treatment $n = 4$, and for the partially harvested treatment $n = 8$. The * indicates that for 2005 the two treatments were significantly different ($P = 0.0104$).

Treatment	Year			
	1994	1995	1999	2005
Unharvested	3.90 (0.36)	3.97 (0.35)	4.59 (0.50)	5.00 (0.22)*
Partially harvested	3.78 (0.10)	3.30 (0.11)	3.85 (0.28)	3.13 (0.16)





Session 5

Modelling Complexity

An Overview of Options for Modelling Complex Stand Structures

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Introduction

The purpose of this keynote address is to provide an overview of options for modelling complex stand structures and to set the stage for the more detailed presentations that follow describing work aimed at developing models that accommodate a range of species compositions and stand structures. Increasing emphasis on ecosystems management and silvicultural systems that maintain natural forest structure and dynamics has resulted in a need to quantitatively describe stands of a complex nature. Complex stand structures—characterized by species, vertical, horizontal, and spatial heterogeneity—are inherently difficult to quantify and model. The previous two sessions of this conference have focused on measuring complexity; the focus of this session (Session 5) is modelling stands of complex structure. Forest management decisions rely on information about both current and future resource conditions. Forests are dynamic biological systems that are continuously changing, and it is necessary to project these changes to obtain relevant information for prudent decision making.

Past Work in Forest Stand Modelling

A great deal of emphasis has been placed on modelling the development of pure, even-aged stands. Models commonly used for forest management purposes fall into two general categories: whole-stand models and individual-tree models. (Additional information about growth and yield models can be found in Avery and Burkhart, 2002; Husch, et al., 2003; Gadow and Hui, 1999; Vanclay, 1994.) In the whole-stand approach quantities such as volume, basal area, and/or number of trees per unit area are forecast. The basic input or predictor variables for these models for even-aged stands are generally age, site index, stand density (numbers of trees per unit area for plantations; basal area for natural stands), and management treatments. Approaches to predicting stand growth and yield that use individual trees as the modeling unit are referred to as "individual-tree models." The components of tree growth (e.g., diameter increment, height increment) plus estimates of mortality are commonly linked together in these models through a computer program which simulates the growth of each tree and then aggregates these to provide estimates

of stand growth and yield. The predictor variables are typically age, site index, and trees per unit area. If the model is spatially explicit, tree coordinate locations are also required and a measure of point density ("competition index") is included. Most individual-tree models allow simulation of a number of management treatments.

Modelling the growth and yield of uneven-aged stands has received much less attention than that of even-aged stands. There has, however, been increased interest in modelling uneven-aged stands in recent years using both individual-tree and stand-level approaches. Peng (2000) provides an in-depth review of the literature regarding growth and yield models for uneven-aged stands, discusses types of models and their merits, and reports recent progress in modelling the dynamics of uneven-aged stands.

Options for Modelling Complex Stand Structures

Because of the great variety of species mixes and stand structures that might be desired, new and innovative approaches to data collection and modelling will be required in order to develop reliable stand development models. The typical approach taken in past growth and yield studies was to define a population of interest, obtain a sample from the defined population, and estimate coefficients in specified equation forms. Obviously, it will not be possible to sample all species mixtures and stand structures of interest. Thus, carefully designed data collection efforts will be required in order to model adequately the full range of conditions of interest. Plots in existing stands will be required, but such plots alone will not likely be fully adequate for modelling purposes. Designed experiments, with controlled mixtures and a range of stand structures, will be needed to test hypotheses and to develop robust prediction equations.

As an initial step, existing growth and yield models, based on data from simpler stand structures, might be used—perhaps after some modification—for simulating development of more complex stands. In the process of developing reliable growth and yield models for forest management, we have learned a great deal about the relationships of tree growth

and stand development to site quality, competition for site resources, and management interventions such as thinning, control of competing vegetation, and nutrient amendment applications. The basic knowledge and quantitative relationships developed for traditional forest management purposes provide a firm foundation and starting point for developing preliminary estimates of stand dynamics for alternative silvicultural systems.

Models such as the Forest Vegetation Simulator (FVS)² that do not rely on age or site index for stand projection are quite readily adapted for projecting a wide range of stand structures, and examples will be presented in this session. Growth response data and modelling experience gained from studies in even-aged monocultures can also be of value as modifications are made to extant models and as field studies are designed and installed to obtain the empirical data needed to further calibrate and refine models for new stand structures.

In addition to modifying and extending current stand modelling structures, a more ecologically-based approach may prove necessary to incorporate the generality desired. Levins (1966) argued that modellers of population biology strive to maximize simultaneously three desirable properties of a given model: generality, reality, and precision. In any one model, he asserted, one may sacrifice one of these desired properties to achieve a higher level of the other two. In traditional growth and yield models, generality has been sacrificed for increased reality and precision. In light of the objectives of past work in growth and yield modelling, this is a reasonable strategy. However, for models involving complex stand structures, it may be desirable to emphasize generality and reality at the expense of precision. Models that provide realistic estimates for a wide range of options seem a reasonable starting place, as opposed to models of high precision for a narrower range of conditions.

In addition to quantitative information on stand dynamics (i.e., the growth, mortality, reproduction, and associated changes in the stand), simulators for

complex structures should incorporate visualization capabilities. Visualization is a powerful tool for understanding forest stand dynamics and improving management decisions. With a visual image of the forest stand at various stages of development, land managers can more easily grasp the need for, and consequences of, management actions (Roth and Finley, 2007).

Conclusions

In conclusion, evaluation of the full spectrum of silvicultural and management options of contemporary interest requires models that incorporate more generality than what is available in traditional growth and yield models. Development of models that can reliably simulate dynamics of stands of complex structure will require innovative approaches to data collection and modelling. The data bases gathered and the models that have been promulgated to support management for wood production objectives can, however, provide valuable insights into growth relationships for varying species, site conditions, and stand densities. Thus, these models, with perhaps some modification, can be used for initial estimates of stand dynamics while data are being collected in more complex stand structures in order to refine and extend modelling capabilities.

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² An overview of FVS and current information on FVS variants may be found on the World Wide Web at: <http://www.fs.fed.us/fmrc/fvs>.

Effects and Correction of Sampling Error in Individual Tree Mortality Models

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Introduction

Many regression-based forest simulation models include predictor variables that account for competition, such as trees per acre, point basal area (PBA) or point basal area in larger trees (PBAL). It is a common practice in forest inventories to estimate these variables with a single measurement per plot. These competition variables measured at a single point are assumed to be a good estimate of the competition variables for all the trees in the plot. However, the trees that are far from the centre of the plot can have a very different PBA or PBAL from the ones measured at the centre of the plot. The variance of the error varies with the size of the plot and with the distribution and size of the trees.

If ignored this sampling error can have significant effects. During model fitting ignoring sampling error can result in the underestimation or overestimation of the significance of predictor variables. This can lead to the exclusion of important explanatory variables in model development. When models built ignoring sampling error are used to predict stand characteristics, the results obtained can be biased. This bias increases when the spatial complexity of the distribution of tree sizes and species increases (Pukkala 1990, Stage and Wykoff 1998).

Recently, methods have been proposed to address the problem but have been confined to the linear statistical model (e.g., the Prognosis large-tree diameter equation; Stage and Wykoff 1998). We present an errors-in-variables (EIV) methodology to correct the bias in parameter estimation due to sampling error for an individual tree mortality model constructed with logistic regression.

For nonlinear models, the most recent literature describes five main approaches for reducing measurement error bias. They include: regression calibration (Carroll and Stefanski 1990), simulation extrapolation (Cook and Stefanski 1994; Stefanski and Cook 1995), score function methods (e.g. Nakamura 1990; Stefanski 1989), likelihood and quasilielihood (e.g. Carroll et al. 1984; Wang et al. 1996), and

Bayesian methods (Gustafson 2004). However, one of them have stood out as widely applicable, effective and fairly well investigated (Pierce and Kellerer 2004). One of the most important advantages of this method is that once the variable measured with error is replaced by the corrected variable, the data can be modelled as if the error does not exist. In other words, a model can be fitted with the usual or preferred method. This is a very desirable characteristic since it implies that the model is parameterized with the corrected variable and the solution is universal.

Material and Methods

The data for this preliminary study was obtained from the USDA Forest Service Region 1 Permanent Plot Program. This dataset (Froese 2003) included data deemed of adequate state for publication by the Forest Service as of December 2002, which included areas on Idaho Panhandle (Kanisku, Coeur d'Alene and St. Joe), Flathead, Kootenai and Lolo National Forests. A total of 34,243 tree measurements across 189 stands were available that had two observations in time and were alive at re-measurement 0 (establishment). Mortality was observed at re-measurement 2 in 1,504 (4.4%) of the trees. The survey design includes a control and several treated clusters of plots where measurements are made on individual tree attributes, including species, diameter, and height.

The key idea of regression calibration is to predict the unobservable predictor $\mathbf{X}$ using the correspondent surrogates $\mathbf{W}$ (observation related with $\mathbf{X}$) and $\mathbf{Z}$ (error free variables). Applied to individual tree mortality models this means that we use the measured PBA, basal area of larger trees in the vicinity of the trees or stand basal area (SBA) and the rest of the assumed error-free variables (diameter at breast height, crown ratio, etc.) to predict the correspondent real value of PBA, BAL or SBA.

We have adopted the same procedures for estimating the sampling variance (Σ_{uu}) as developed by Stage and Wykoff (1998).

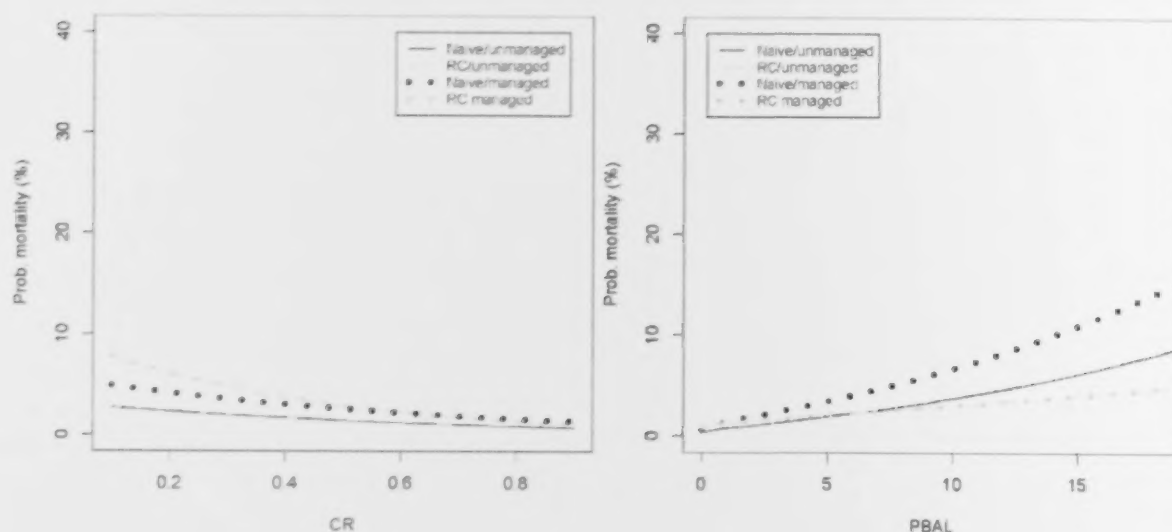


Figure 1. Sensitivity graphs for lodgepole pine.

Results

Preliminary results show that in the naïve approach (ignoring the sampling error) trees in managed stands have, in general, higher probability of mortality than in unmanaged stands. This difference tends to decrease in the regression calibration (RC) approach.

The residual deviance under the regression calibration approach is always higher than under the naïve approach, except for western hemlock. However, this increase in residual deviance is not necessarily accompanied by a decrease in the overall goodness-of-fit.

The sensitivity graphs for lodgepole pine (Figure 1) show a decrease in the slope of the PBAL curve for the RC approach and an increase in the crown ratio (CR) slope for the RC approach versus the naïve approach.

Conclusion

Despite limited data, RC showed promise. Many of the expected benefits seemed apparent in these very preliminary model calibrations.

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Calibrating a Model for Even-Aged Stands of Stone Pine (*Pinus pinea* L.) to Complex Multi-Aged Structures

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Introduction

Stone pine (*Pinus pinea* L.) is a typical shade-intolerant Mediterranean species, occupying in Spain more than 400,000 ha. The main objective in the management of stone pine stands combine two main commercial productions, timber and pine nuts with other interesting social aspects: soil protection, recreational use and biodiversity conservation. To attain these objectives stone pine stands have been usually managed as even-aged structures maintaining low stocking densities to increase cone production. Despite this, competition for water resources, anticipated recruitment, failure in natural regeneration, grazing and the maintenance of old large cone producer trees have sometimes resulted in a natural evolution of the stands to an uneven-aged structure. On favorable locations, forest managers have proposed a successful management schedule based on the establishment and preservation of a multi-aged complex structure.

Up to the present several modeling tools have been developed to help the management of even-aged stone pine stands, including PINEA2 (Calama et al. 2007a), an integrated single-tree level multi-objective model. In the present work data from four uneven-aged stone pine stands are used to calibrate and validate PINEA2 for its use on complex structures. Main part of the mathematical functions included in PINEA2 were formulated as multilevel mixed models, including random components acting at plot and tree levels, which were then explained by including typical even-aged stand and tree covariates. The proposed approach for calibration shown in the present work is based on predicting tree and stand random components for the uneven-aged conditions using the empirical best linear unbiased predictors (EBLUP) theory. The calibrated model for multi-aged structure was used to compare even and uneven-aged management schedules in terms of cone, timber yield and structural diversity along a productive cycle. Finally, the calibrated model was used to define a sustainable management schedule for multi-aged stands of stone pine.

Material

The study material included four plots (VA-1, VA-2, AV-1, AV-2) installed on uneven-aged stands of stone pine located in Central Spain. Plot area ranges from 2,800 to 4,800 m². Within the plots coordinates for each tree higher than 20 cm were recorded. For trees with breast height diameter larger than 5 cm, total height, height to crown base, crown diameter, bark thickness, total age and the past five years radial growth were measured. In smaller plants only total height and crown diameter were measured. Multi-aged structure is assessed since plots show several different age and diameter classes (Figure 1). Actual management schedule in these stands is not orientated to get an ideal reverse-J structure in age class distribution, but to maintain standing very old trees with large cone productions regarding the development of younger strata and helping recruitment installation within the gaps. To attain this, selection cuttings are carried out within a 25 years rotation, extracting all non-vigorous trees and all young trees competing with an old great fruiter tree.

Methods

The model PINEA2 is divided into three different modules (site quality, state and transition) including several mathematical relations: site index (ADA formulation), height-diameter, crown dimensions, stem curve, cone production, biomass fractions and single tree diameter increment function. For adapting PINEA2 to multi-aged structures, following steps have been proposed:

- Site index for multi-aged structures was defined by averaging the value of site index estimated per different age classes.
- Height-diameter and five year diameter increment functions in PINEA2 were formulated as multilevel mixed models including plot and tree level random components. Since we had measurements of those covariates in multi-aged plots, it was then possible to calibrate these functions for those conditions:
 1. We considered the basic original structures of the relations defined for even aged-stands, only

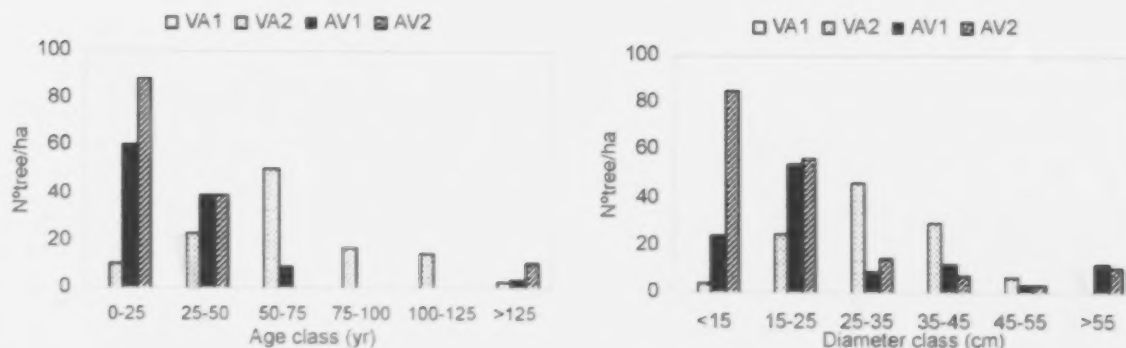


Figure 1. Observed frequencies per age (left) and diameter (right) classes.

including as explanatory covariates single tree attributes (diameter) as well as plot and tree level random components, and we predicted random plot and tree components for multi-aged plots, following EBLUP theory (Vonesh and Chinchilli 1997).

2. Predicted EBLUPs were then contrasted with the original distributions for even aged stands to detect possible patterns of deviation.

3. The possible covariates explaining variability at tree or stand level on multi-aged plots were identified. These covariates must be among those that can be computed on this type of stands: range of diameter distribution, stand attributes per age or diameter class, tree level distance dependent and independent competition indices, structural diversity indices...

- Cone production model for even-aged stands (Calama et al. 2007b) should be reformulated not considering typical even aged explanatory covariates, as stand density, age or site index.
- Original stem curve function, crown dimension relations and biomass fractions equations, constructed and validated for even aged stands, were considered valid for multi-aged structures.

Results and Discussion

- Estimates for site index in multi-aged structures were consistent through the range of ages within the plots, so the proposed method is considered valid.
- Basic five year diameter increment function, only including as explanatory covariate the natural logarithm of breast height diameter, was calibrated to multi-aged plots by predicting EBLUPs at plot and

tree level. Predicted EBLUPs were within the range of distribution calculated for even-aged stands

- No stand covariate was related with plot level random components for diameter increment, so for practical use of the model we proposed calibration using a small additional sample of increment measurements (taken with an increment borer).
- Best covariates in explaining tree level random components for diameter increment were crown ratio, influence area overlap indices and horizontal and vertical differentiation indices (Gadow 1993). For practical use of the model tree level random components can be estimated using these indices together with a stochastic component.
- Height-diameter relation for multi-aged structures is reformulated to pass through the point [maximum height – maximum diameter] computed per diameter class.
- Proposed cone model for multi-aged structures includes as explanatory covariates tree section and an ecological based stratification of the territory

Conclusions

We have proposed an approach for calibrating a single tree level model for even-aged stands to multi-age condition. Main use of the calibrated model is to compare even-aged and multi-aged schedules of management in terms of cone and timber production. In the proposed simulation, maintenance of multi-aged structures leads to larger productions of cones, while there is a loss in timber yield.

IVY: An Individual-Tree Growth Model for Complex-Structured Stands

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Introduction

Accurate, long-term forecasts of stand structure, composition, growth and yield are critical to sustainable forest management. The task of forecasting stand dynamics has become more challenging, because evolving forestry practices are leading to stands with more complex structure (Groot et al. 2005), including mixed species composition, and heterogeneous size and spatial distribution.

Groot et al. (2004) reviewed modelling approaches for complex stands in the eastern Canadian boreal forest. Since whole stand models are not sufficiently flexible, individual-tree empirical models, based on statistical relationships of growth to tree and stand characteristics, have been used to forecast stand dynamics. Individual-tree models are prone to aggregation and propagation of error, however, and forecasts beyond 20 or 30 years may be unreliable. Mäkelä (2003) emphasized the need to incorporate coarse-level constraints into models to ensure long-term accuracy and model robustness. Resource constraints are well-suited to this role (Mäkelä 2003), and the light resource provides a particularly effective constraint (Groot et al. 2004).

Consequently, we are developing an individual-tree based growth model, IVY, to provide more robust, long-

term forecasts of stand structure, composition, growth and yield. The model uses a light-capture based approach to predict the volume increment of individual trees (I_v).

This presentation describes the structure of the IVY model and some of its data requirements. The presentation also discusses progress in the development of the IVY model software.

Materials and Methods

The IVY model relates individual tree volume growth to the amount of light captured by the crown during the growing season. The finite amount of light available for interception by trees in a stand imposes a constraint on stand-level growth, helping to control error. The IVY model uses a ray-tracing algorithm to compute light interception for asymmetric crowns with shapes ranging from neiloid to cylindrical (Groot 2004). Volume increment efficiency (VIE), the amount of stem volume growth per unit of intercepted light, is required to translate light interception values into volume growth estimates. VIE estimates have been obtained from field measurements of light interception (Groot 2005) and volume growth for *Picea mariana* and *Populus tremuloides* (Groot and Saucier, in preparation).

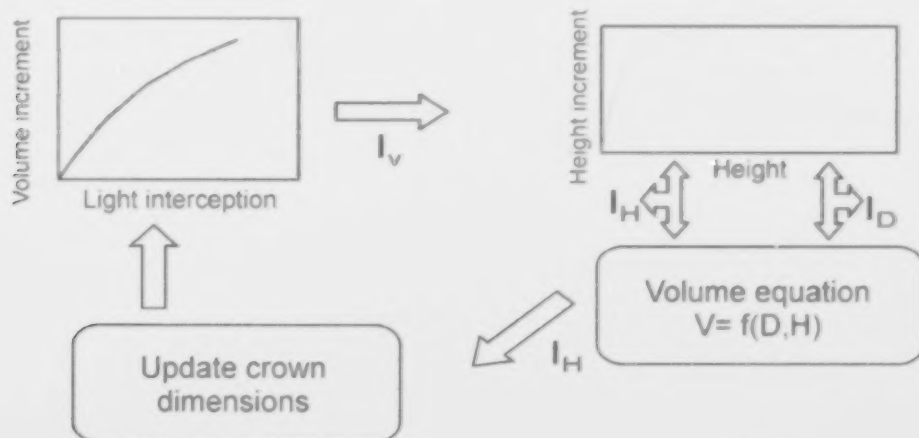


Figure 1. Structure of the IVY model.

Results

The structure of the IVY model is depicted in Figure 1. Values of I_v are computed as the product of (i) the amount of light captured by the crown during the photosynthetic season, and (ii) the *VIE*. Height growth is obtained from the simultaneous solution of volume [$V = f(H, D)$] and height increment equations [$I_H = g(I_v, H, SI)$]. The resulting height increment determines the vertical and radial expansion of the crown. Updated crown dimensions are used to determine light interception for the next model cycle. Because the IVY model is driven by light interception, modelling crown dynamics (height growth, crown radial growth, and crown rise) is a key model component.

For *P. mariana*, *VIE* varies strongly among site types (from 0.071 dm³ GJ⁻¹ on poor-quality peatland sites to 0.345 dm³ GJ⁻¹ on fertile mineral soil sites) and is linearly related to site index.

Discussion

The light-capture based modelling approach is conceptually more straightforward and is more closely related to tree growth processes than empirical models. Resulting stand level forecasts should be robust, since light availability exerts a well-defined constraint on growth. We expect that the model will be applicable to a wide range of stand structures and site conditions. The approach is versatile in that changing environmental conditions and some disturbances can be realistically represented. For example, the effects of climate change would be represented by a longer growing season, and by increased light-use efficiency

relating to increasing CO₂ concentrations. Defoliation by insects would be represented by increasing light transmission through crowns.

The IVY model is being programmed into user-friendly software using Visual Basic 2005. Completion of the IVY software will facilitate the incorporation of *VIE* data for additional species resulting in a model that is applicable across the Canadian boreal forest. Because of the emphasis on crown dimensions in IVY, there is potential to extend model outputs to include crown-related wood quality attributes such as juvenile wood and heartwood distribution and the distribution and frequency of knots.

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Coupling a Boreal Mixedwood Silvicultural Experiment With Long-Term Stand Modelling Using SORTIE-ND

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Field experiments were established in even-aged, aspen-dominated mixedwoods in 1998 in the Lake Duparquet area (NW Quebec) to test the operational and biological feasibility of better integrating natural stand dynamics (particularly the transition from intolerant hardwoods to mixed woods to conifer-dominated composition) into silviculture scenarios. Short-term monitoring of these experiments has provided information on changes in environmental conditions induced by a gradient of stand openings created by four harvesting treatments (clear-cuts, two intensities of partial cuts and controls), as well as on immediate response of understory growth, conifer recruitment, and tree mortality and woody debris dynamics. In order to project possible long-term

outcomes of tested treatments (and other variants), SORTIE-ND, a spatially-explicit, stand-level model that is largely calibrated for our study area, is being used to compare changes in stand structure and composition over a 100-year period. The treated stands originated from a fire in 1923 and simulation results will be referenced with data from permanent sample plots situated in a nearby forest that originated from a fire in 1823. Simulations suggest that partial cutting can increase structural complexity and accelerate transition from a near normal diameter distribution to an irregular structure by stimulating softwood recruitment and possibly retarding break-up of the aspen cohort.

Prognosis^{BC}: An Adaptation of a Single Tree Model to Southeastern British Columbia

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Introduction

Mixed-species and/or multi-aged stands (complex stands) are common in southeastern and central British Columbia (BC), especially in more accessible and visible areas. The use of some form of partial cutting in this type of stand, for aesthetic, habitat, watershed, or other considerations, has been increasing. Partial cutting generally increases or at least maintains the structural and spatial complexity of such stands, increasing the difficulties in obtaining reliable predictions of future stand development.

The Prognosis suite of models, known as the Forest Vegetation Simulator (FVS) in the United States (US), was originally developed to assist in projecting the complex stands found in the northern Rocky Mountain region of the US (Stage 1973; Wykoff *et al.* 1982). The growth and yield component of this suite of models forecasts future stand conditions based on the expected growth and mortality of individual trees (non-spatial), allowing the user to simulate a wide range of harvesting strategies. Furthermore, the model's architecture readily supports a number of extensions or add-on features, ranging from parallel processing (the simulator processes multiple stands in a landscape setting) and events monitoring (which allows the user to specify certain stand conditions for a management activity to occur) (Crookston and Stage 1991) to extensions for modeling various fire, insect and disease impacts (e.g., Beukema and Kurz 1994).

The considerable work already completed on FVS, and the similarity of the stand conditions in the northern Rocky Mountain region of the US to those found in southeastern BC prompted the BC Ministry of Forests and Range to adapt the northern Idaho variant of FVS for use in BC. This paper presents a chronology of the development of Prognosis^{BC}, including the modelling approaches used in the adaptation.

Model Development Chronology

An initial step in extending Prognosis northward was mapping the BC Biogeoclimatic Ecosystem Classification (BEC) units in southeastern and

central BC (Meidinger and Pojar 1991) onto their corresponding Daubenmire habitat types represented in the northern Idaho variant (Sargent and McKenzie 1997). BEC units represent groups of ecosystems under the influence of the same regional climate. For example variants of the Interior-Douglas-fir dry cool (IDFdk) BEC subzone were mapped to corresponding phases of the Douglas fir/pine grass habitat type. Version 1.0, released in 1998, used BC BEC zones, included a graphical user interface, and allowed for input and output in metric units. The tree growth and mortality components were not changed, but the Northern Idaho taper functions were replaced with BC taper functions (Robinson 1997).

Version 2.0 was released in 2000 with two significant changes: 1) the self-calibration processes for dbh (diameter outside bark at 1.3 m above ground) and height growth models were implemented; and 2) BEC-based stand-level mortality models were developed (Zumrawi *et al.* 2002). Repeated measurements on selected permanent sample plots (PSPs) from a wide range of BEC subzones were used to provide initial tree and stand conditions and 10-year diameter increments. Using the self-calibration process described in Wykoff *et al.* (1982), growth predictions of each species were scaled to match the PSP growth data. For the individual tree mortality models, logistic regression was used along with PSP data to obtain fitted models by species and BEC subzones (Temesgen and LeMay 2000). Additional temporary plot data were used to estimate maximum basal areas by BEC site series. This maximum basal area was used along with the logistic mortality models to simulate mortality.

One of the issues not addressed in Version 2.0 was predicting the amount and composition of natural regeneration following partial harvests. Historical PSP data lacked measurements on natural regeneration and small trees, and other natural regeneration data collected on temporary sample plots were limited in scope. Therefore, provisions were made in Version 2.0 (and Version 1.0) for the model user to specify the amount and composition of natural regeneration following partial harvesting through a graphical user interface.

In Version 3.0, released in 2004, new tree-level growth models were implemented. Nonlinear models of large tree (dbh > 7.5 cm) dbh and height increment, and small tree height increment models were developed for a wide range of subzones in the Interior Douglas-fir (IDF) and Interior Cedar hemlock (ICH) BEC zones (Zumrawi *et al.* 2005). Large tree dbh growth was modeled as a function of initial dbh, site factors, stand density and non-spatial measures of the relative position of the subject tree in the stand, using PSP data. Small tree height growth was modeled as a function of initial height and non-spatial measures of the relative position of the subject tree in the stand. Since historical PSP data lack measures of small trees, height increment measures on temporary sample plots were used.

A novel approach using most similar neighbour (MSN) multivariate imputation was used to estimate natural regeneration following partial harvesting (Hassani *et al.* 2004). This approach allowed for the simultaneous estimation of regeneration of all sizes and species, based on matching overstory characteristics and selecting a "neighboring" plot with measured regeneration from a database. However, this feature is still in testing and was not fully implemented with Version 3.0.

Model Validation

Data from 30 PSPs in the dry belt of IDFdk3 (dry cool 3) BEC subzone were used to validate Version 3.0 of the Prognosis^{BC} model. Twenty-four of the 30 plots constitute a spacing trial and include a range of spacing treatments. The remaining six plots were established in a variety of stand structures. Tests of accuracy and precision were used to compare 11-year model-predictions with observed plot summaries. Regression-based tests of equivalence (Robinson *et al.* 2005) were included in the validation study (Zumrawi *et al.* 2006). Overall, the model performance was found to be within acceptable limits for growth and yield predictions in the IDF BEC zone.

Conclusion

The approach used in Prognosis allows for modelling tree growth in complex, multi-aged, and multi-species stands, under partial cutting and other disturbances. Prognosis^{BC} was calibrated for use in a number of subzones in the IDF and ICH ecological zones.

The model includes a component to estimate regeneration following partial cutting using multivariate imputation, and is currently being extended to predict natural regeneration following mountain pine beetle attack of lodgepole pine (*Pinus contorta* var. *latifolia*) dominated stands. Other growth components of Version 3.0 are also being validated, and extensions to other BEC zones are in progress.

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Modelling Height-Diameter Relationship for Tree Species Grown in Mixed Stands

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Introduction

Knowledge of diameter at breast height (DBH) and total tree height is fundamental to both developing and applying many growth and yield models. DBH of a tree can be measured quickly, easily, and accurately, but the measurement of total tree height is relatively complex, time consuming, and expensive. Therefore, with many permanent and temporary sample plot systems, DBH is conventionally measured for all trees sampled, but height is measured for only a sub-sample of trees selected across the range of diameters observed. Height-diameter relationship models are then used to estimate the heights of trees measured only for diameter. A number of height-diameter equations have been developed using only DBH as the predictor variable for estimating total height (e.g., Curtis 1967, Wykoff et al. 1982, Huang et al. 1992, Moore et al. 1996, Fang and Bailey 1998, Peng et al. 2001, Robinson and Wykoff 2004). However, the relation between the diameter of a tree and its height varies among and depends on the growing environment and stand conditions (Sharma and Zhang 2004). For a particular height, trees that grow in high density stands will have smaller diameters than those growing in less dense stands, because of greater competition among individuals (Calama and Montero 2004). These factors indicate that additional predictor variables are required to develop generalized height-diameter models to avoid having to develop individual height-diameter relationships for every stand (Temesgen and Gadow 2004). The objective of this study was to develop height prediction equations in terms of easily measured tree and stand characteristics for eight major commercial tree species grown in Ontario's boreal mixed forest stands. These tree species are: balsam fir (*Abies balsamea* (L.) Mill.), balsam poplar (*Populus balsamifera* L.), black spruce (*Picea mariana* (Mill.) B.S.P.), jack pine (*Pinus banksiana* Lamb.), red pine (*P. resinosa* Ait.), trembling aspen (*Populus tremuloides* Michx.), white birch (*Betula papyrifera* Marsh.), and white spruce (*Picea glauca* (Moench) Voss).

Material and Methods

Data used in this study were obtained from permanent sample plots established and maintained by the Ontario Ministry of Natural Resources (OMNR), Canada. The plots are located across much of the commercially operable forest of northern Ontario.

The data set contained both plot- and tree-level information. The plot-level information included total tree basal area/ha (BA), number of stems/ha (TPH) calculated from trees with DBH ≥ 2.5 cm, and the area of the plot (400 m²). A total of 5,498 plots were included. Mean values of BA, TPH, and stand height (average height of dominant and codominant trees) for these plots were 24.22 m², 2,236, and 15.21 m with their standard deviations 9.81 m², 1,583, and 5.21 m, respectively. Ranges of these stand characteristics were 5.03 to 85.32 m² for BA/ha, 50 to 17,625 for trees/ha, and 3.80 to 33.10 m for stand height. The tree-level information contained tree status (live or dead), origin (natural or planted), species, and DBH, for all the trees, and total height for a subset of trees on a plot. Trees that were dead, defective at DBH, or had a broken top were not used in this study. In total, 6,400 balsam fir, 1,145 balsam poplar, 20,325 black spruce, 20,652 jack pine, 1,005 red pine, 13,211 trembling aspen, 8,462 white birch, and 5,304 white spruce trees were available. In terms of species composition (% of basal area of the species under consideration), jack pine and balsam fir contributed average basal areas of 62.6% (highest) and 12.6% (lowest), respectively, in the plots they inhabited. About half the plots were randomly selected for each species and all the trees from these plots were used to estimate model parameters. The trees in the remaining plots were used for model validation.

Height-Diameter Models

The Chapman-Richards equation recommended by Peng et al. (2001) for jack pine and black spruce trees was:

$$(1) H = 1.3 + a(1 - e^{-\beta D})^{\gamma}$$

where, H = total tree height (m), and D = diameter at breast height (DBH) (cm). In mixed-effects modelling context, Equation (1) with the asymptote and rate parameters expressed in terms of stand height and TPH/BA, respectively, can be expressed mathematically as:

$$(2) h_{ij} = 1.3 + (q + u_i)(SHT_i)^{\delta} \left(1 - e^{-\beta(TPH_i/BA_i)^{\phi}}\right)^{\gamma} + e_{ij}$$

where, β , γ , δ , ϕ , and θ are considered fixed parameters, common to every plot, u_i is a random parameter ($u_i \sim N(0, \tau)$) specific to plot i , h_{ij} and e_{ij}

are the height and error for the j th observation in the i th plot, respectively. τ is the variance for the random-effect, SHT is the stand height and other variables are as defined earlier. Since most of the plots had one measurement, autocorrelation arising from the repeated measurements was ignored. Similarly, some plots only contained a few trees (as low as two). Therefore, within-plot variance-covariance was assumed to be $\sigma_e^2 I$ ($I = n_i \times n_i$ identity matrix). In the case of specifying between-plot variation, there is only one random effects parameter α with the random part u_i . As a result, the variance-covariance matrix (D) of random effects becomes $D = \sigma_u^2$. Equations (1) and (2) were fitted to the model data set using the NLIN and NLMIXED procedure in SAS. In order to examine the impact of the random parameter on the other parameter estimates, the fit for Equation (2) was performed with and without the random parameter, u_i .

Results and Discussion

Table 1 displays the fit statistics (R^2 , MSE, and AIC) for equations (1 and 2) derived from the NLIN and NLMIXED procedures in SAS. Equations (2) and (1) had the best and poorest fits, respectively. Equation (1) had the largest variation in R^2 and MSE across species. The R^2 varied from 0.757 (jack pine) to 0.901 (balsam poplar) and the mean square error (MSE) varied from 2.97 (balsam fir) to 9.55 (red pine). On the other hand, the R^2 and MSE varied from 0.898 (black spruce) to 0.956 (jack pine) and from 1.43 (jack pine) to 2.67 (red pine), respectively, for Equation (2). Similarly, AIC decreased from Equations (1) to (2) for all species but the largest decrease was in the case of jack pine trees. In the mixed-effects modelling approach, height can be predicted i) by assuming the random parameters are zero (fixed-effects response), ii) by predicting plot level random parameters using height information (if available) of a sub-sample of trees from the plot (calibrated response). Height prediction bias (observed - predicted) was calculated for each fixed and calibrated response for the validation data sets for all tree species.

These values were smaller for calibrated response than for fixed response except for jack pine. Overall, average bias and its standard deviation were slightly smaller for calibrated response than for fixed response for all DBH and density classes for all species.

Conclusion

The Chapman-Richards function was modified to model the height-diameter relationship of eight major commercial tree species growing in the boreal forests of Ontario, Canada. The asymptote expressed in terms of stand height (average of dominant and codominant heights) and the rate parameter expressed as a function of stand density and basal area, resulted in the best model in terms of fit characteristics (R^2 , MSE, and AIC) and prediction accuracy for these tree species.

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Table 1. Fit statistics (R^2 , MSE, and AIC) for equations (1) and (2) by species

Equation	Goodness of fit	Balsam fir	Balsam poplar	Black spruce	Jack pine	Red pine	Trembling aspen	White birch	White spruce
1	R^2	0.858	0.901	0.834	0.757	0.822	0.857	0.802	0.885
	MSE	2.97	4.06	3.76	7.34	9.55	5.94	3.84	3.30
	AIC	13730	2587	48243	52752	3397	34472	18960	11515
2	R^2	0.895	0.955	0.898	0.953	0.951	0.953	0.884	0.917
	MSE	2.20	1.88	2.32	1.43	2.67	1.97	2.25	2.39
	AIC	12680	2119	42659	34889	2551	26242	16541	10592

* Computed as $(1 - \text{residual sum of squares}/\text{corrected sum of squares})$

Validating the Gap Model ZELIG for an Uneven-Aged Mixedwood Forest Type in Southeastern Canada

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Introduction

Forest growth models include traditional empirical growth and yield models and gap models. Growth and yield models aim at predicting tree and stand volumes or the effects of silvicultural treatments. However, the level of confidence of their predictions is limited to short simulation horizons and the range of stand conditions within which they are derived (Landsberg 2003). Also, they focus on the growth prediction of the dominant tree layer, mostly in even-aged pure stands, and have limited capacity to predict the long-term effects of disturbances in all tree layers, such as the potential succession pathways following gap dynamics. Gap models are characterized by a stronger mechanistic or descriptive basis than growth and yield models (Larocque 2007). As they simulate the growth and mortality of individual trees, seedling establishment and the transition from seedlings to trees, gap models are well equipped to predict the growth and succession of uneven-aged mixed stands characterized by complex structures. However, the validation of gap models still remains a problem, as few long-term historical datasets exist. The objectives of the present study were to examine a case study of the validation of the ZELIG model for an uneven-aged mixedwood forest type in southeastern Canada and to identify research needs.

Materials and Methods

ZELIG, a gap model originally developed by Urban (1990), contains several modules to simulate individual tree growth and mortality and seedling establishment. Monthly temperature and precipitation data (mean and standard deviations) are provided as input and annual random variations are generated. For each tree, diameter increment is predicted by computing its potential growth rate reduced by site constraints, which include available relative photosynthetic active radiation, temperature, and indexes based on soil moisture and nutrient availability. Seedling establishment is also modelled by taking into account understory light conditions and soil basic characteristics.

Historical data were obtained from the Lake Édouard Experimental Forest (LEEF) data bank for the balsam fir-red spruce-yellow birch forest type (Archambault et al. 2003). The LEEF is located in the La Mauricie National Park in southeastern Canada. Sample plots measuring 405 m² were established in 1936 and remeasured in 1946, 1956, 1967, 1995, 2001, 2003 and 2004. Dbh was measured on individual trees and tallied by 2.54 cm (1 in.) classes. Thus, it was possible to compare predictions and observations over a 60-year period.

Results

There was a good agreement between predicted and observed basal area for red spruce (*Picea rubens* Sarg.), yellow birch (*Betula alleghaniensis* Britton), balsam fir (*Abies balsamea* (L.) Mill.), northern white cedar (*Thuja occidentalis* L.) and red maple (*Acer rubrum* L.) over a 60-year period (Figure 1). For white birch (*Betula papyrifera* Marsh.), predicted and observed basal areas were close for the first 10 years only. Despite the fact that substantial differences were obtained thereafter, the predicted pattern of change was consistent with observations: ZELIG predicted the decline and disappearance of white birch, but much later than the observed decline and disappearance. Predicted and observed stand densities were relatively close in the first 10 years for all dbh classes, except for the 10 cm dbh class (Figure 2). However, large differences were obtained in years 31 and 67, particularly in the 10 and 20 cm dbh classes.

Discussion

Long-term historical data are undoubtedly useful for the validation of gap models. For the present study, they increased the level of confidence in the prediction of long-term changes in the growth and mortality of most species in the dominant tree layer of uneven-aged complex stands. White birch is the only species whose predicted basal area differed considerably from observations. Nevertheless, its predicted disappearance was consistent with its life history,

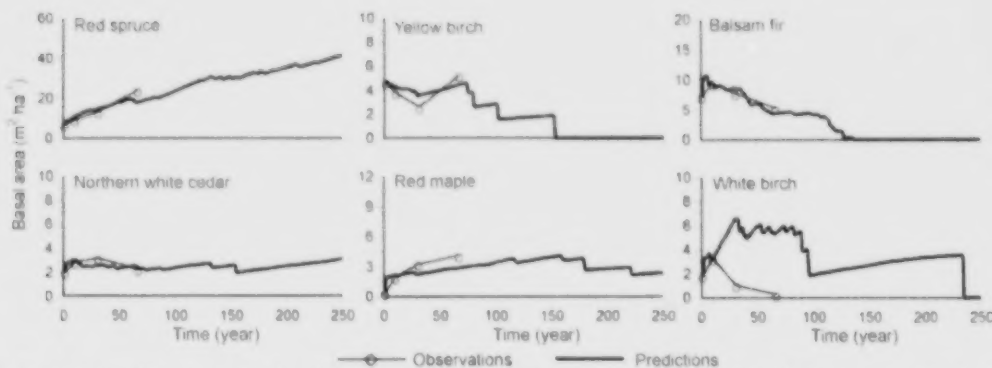


Figure 1. Comparison of mean predicted and observed basal area in red spruce-balsam fir-yellow birch uneven-aged mixed stands in southeastern Canada

as it is a transitional species with a relatively short life span (Safford et al. 1990). The large differences between predicted and observed dbh distributions in the lowest dbh classes in years 31 and 67 most likely resulted from a poor prediction of the transition from seedling to tree status. These results do not invalidate the mechanistic basis of a model such as ZELIG with respect to the prediction of seedling establishment. In fact, this model is designed around a biologically consistent representation of seedling establishment and growth. However, the lack of information on seedling dynamics lowers the confidence in the results of long-term predictions. Typical historical datasets seldom contain information on seedling establishment and growth, as they were designed by forestry agencies to include information on stems of commercial size.

In addition, there is still little information on seedling establishment and the factors that affect the transition from seedling to tree status for the majority of tree species. As gap models may be used to simulate forest succession over long time horizons (e.g., Miller and Urban 1999), further research on seedling dynamics is needed to improve the capacity of gap models to predict potential succession pathways with confidence.

Conclusion

The evaluation of the potential long-term effects of disturbances on long-term succession must be conducted when the basic principles of forest ecosystem management are applied. Gap models are well adapted to simulate the growth of uneven-aged mixed complex stands. However, further research is needed to better predict seedling dynamics.

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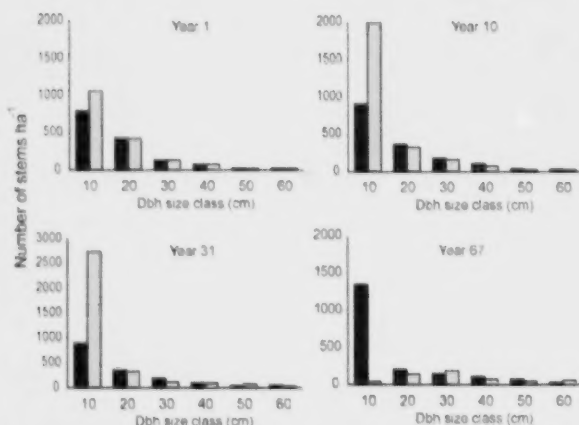


Figure 2. Observed and predicted dbh distributions in red spruce-balsam fir-yellow birch uneven-aged mixed stands at four projection years in southeastern Canada⁴.

⁴ This figure was adapted from an article published in *Ecological Modelling*, vol. 199, Larocque, G.R., L. Archambault, C. Delisle, Modelling forest succession in two southeastern Canadian mixedwood ecosystem types using the ZELIG model, pages 350-362, Copyright Elsevier 2006.



**Complex Stand Structures:
Economic Consequences,
Operational Challenges and
Decision-Support Tools**

Estimation of Crown and Wood Characteristics in British Columbia

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Forest managers are concerned that fast-growing trees in our intensively managed second-growth forests produce lumber of inferior quality. Consequently, research attention is focusing on how tree growth affects wood properties. For over a decade, Research Branch has collaborated with other agencies including FORINTEK Canada Corporation, Pulp and Paper Research Institute of Canada (PAPRICAN, the University of British Columbia (UBC), and several industry and Ministry partners, to collect data on the growth and wood properties of some of BC's most important commercial tree species. Large co-ordinated projects began with the Douglas-fir Task

Force in 1985 and similar projects followed for western hemlock in the mid 1990s and most recently lodgepole pine. A proposed project to study white spruce in the interior is under review.

Prediction models of branch and foliage distributions, branch growth, knot sizes, and wood characteristics (relative density, microfibril angle and tracheid length) have been developed. This presentation will summarize the research methodology, introduce the capability of our systems and review findings from the various projects. Extrapolations to complex stands will be hypothesized.

Projected Growth of Young Pine Stands Near Prince George: Post-beetle

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Introduction

British Columbia's lodgepole pine (*Pinus contorta* Dougl. Ex Loud. Var. *latifolia* Engelm.) forests are experiencing a mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (MPB) epidemic. It is predicted that 80% of the susceptible (mature) pine will be killed and the Prince George AAC (allowable annual cut) will fall below 75% of the pre – MPB AAC (Eng et al. 2004, 2005). The post-beetle mid-term AAC also depends on there being no MPB attack in stands ≤60 years old (age classes 1, 2 and 3) (Eng et al. 2004, 2005).

However, this does not appear to be the case in young stands (MacLauchlan 2006, Pousette and Hawkins 2006). Depending on the extent of MPB-induced mortality and subsequent forest growth, the mid-term AAC could be depressed further. The impact of MPB attack on the stand depends in part on the species composition of the tree layer, the abundance, species composition, health and vigour of regeneration under the main canopy (secondary structure), and the ability of the regeneration to respond to release (c.f. Griesbauer and Green 2006).

There are three broad options for forest managers to address the timber supply issue: leave the stand alone and allow stand dynamics to proceed; underplant (fill plant) the stand to enhance stocking and seedling vigour; clear the land (possibly log if age class 3) and plant to start a new plantation. There are social, biological, and economic benefits and costs associated with each scenario. For our purposes, the 'right' decision is the one which results in the best economic return at planned rotation age (PRA): usually 75 years in central BC.

The objectives were to quantify MPB attack, document beetle induced changes in stand structure and composition, assess the amount and quality of regeneration in young stands, model future growth, and make management recommendations.

Materials and Methods

In 2005, 92 pine leading age class 1 to 3 stands were sampled in drier sub-zones west of Prince George. Age class 1 and 2 stands are plantations while age class 3 stands regenerated naturally after fire. A subset of the 2005 polygons was re-assessed for MPB in 2006.

Ninety additional young pine-dominated stands were sampled in wetter sub-zones east of the city in 2006. Sampling followed the protocol of Rakochy (2005).

Data collected for each plot were: forest cover, polygon number, GPS location, site series, site index, macro aspect, crown closure, mature tree (defined as dbh ≥ 7.5 cm at 1.37 m height) species, dbh, vigour, stage of MPB attack, and relative crown position. A tree core from the site tree of each plot was used to confirm stand age and productivity (SI_{50}). Height was taken for each site tree. Regeneration (natural or artificial) information included: species, dbh of saplings, height of seedlings and saplings, and vigour of both. Seedlings were regeneration with a height < 1.37 m while saplings had a dbh of < 7.5 cm and a height ≥ 1.37 m. Stocking and species composition by layer (tree, regeneration) was determined for each polygon.

SORTIE-ND (2006) was used to model four stand growth scenarios: (1) no MPB attack (base case); (2) no management after MPB attack; (3) after MPB attack, underplant with 600 sph (300 spruce + 300 pine in the dry area, 600 spruce in the wet area); (4) after MPB attack, clear stand and plant (800 sph spruce and 800 sph pine). Projections were based on current tree lists and run for 100 years. No scenarios were run for age class 1 on the dry sites because of the very low MPB attack rate.

Net present value (NPV) was determined for each scenario. Recommendations are based on sensitivity analysis of NPV at PRA.

Results

Data Collection

Attack rates in 2005 were 0% in age class 1 (0-20 years) and about 20% and 50% in age classes 2 (21-40 years) and 3 (41-60 years). A subset of the 2005 stands was remeasured in 2006. We found re-sampled attack rates of 1, 41 and 62% in age classes 1 to 3, respectively. Attack rates in 2006 origin stands were 8%, 43% and 37% for age classes 1 to 3, respectively. Generally the standard deviation for attack was as large as or larger than the mean. West of Prince George (dry), mean dbh increased with age class while age class 2 had a greater mean dbh than age class 3 in the wet area (east).

The pre-MPB mature layer species composition was similar among age classes and locales (dry, wet): pine stands (> 75%) with minor (< 5%) components of spruce, aspen, paper birch, Douglas-fir or sub-alpine fir.

Sapling and seedling regeneration was plentiful (usually >1000 sph of each) on both dry and wet areas but generally tended to be greater in the wet area. However the standard deviation was usually larger than the mean. Regeneration stocking tended to increase with age class. Spruce, pine and aspen were the main seedling source on the dry area, while spruce, sub-alpine fir, and minor components of the other species occupied the wet area. In the dry area, pine was the most abundant sapling (> 40%) followed by spruce, while in the wet area it was pine in age class 1 and spruce in age classes 2 and 3. Also for some age classes in the wet area, aspen, birch or sub-alpine fir abundance was greater than 10%.

Modelling Example

In the drier areas to the west, age class 2 productivity was not impacted at PRA by MPB attack when attack rates were low (< 30%). Conversely when attack rates were about 60%, the yield loss at PRA was about 75 to 100 m³ per ha and the amount of regeneration in the stand did not appear to significantly influence post MPB stand growth. Generally at attack rates less than 60%, loss of productivity was proportional to MPB attack. When attack rates exceeded 75%, the productivity loss at PRA was greater (100 to 150 m³) and stand growth was positively influenced by the amount of regeneration present.

Only 3 polygons had an improved NPV (MPB NPV – Base NPV) near PRA as a result of the MPB. One stand had a greater NPV before PRA: the MPB enhanced stand value. Generally, under planting or starting again resulted in lower NPV at PRA than did leaving the attacked stand alone.

Discussion

Understanding the potential range of stand responses after MPB attack is crucial in developing management plans. All MPB attack rates for young stands exceed the 0% rate used in AAC projections: therefore current mid-term AAC projections are likely optimistic (*c.f.* Eng et al. 2004, 2005). This makes secondary stand structure an important consideration for management of MPB affected stands. After attack, the residual stands' mature layer was marginally stocked (> 600 sph). At the landscape level, it appears attacked stands are well stocked with regeneration of desirable species: equal amounts of pine and spruce to the west but more spruce than pine to the east. However, the range is large: some stands have no or little regeneration in either layer while others have > 5000 sph.

In age class 2 stands, when attack rates were low (< 30%) the MPB had little impact on yields at PRA: minimal impact on AAC. As attack rates increased PRA yields decreased: the regeneration layer was not able to make up the MPB-induced lost productivity. However when attack rates were > 75% losses were greater but sapling regeneration made a positive contribution to stand yield at PRA (about 40 to 45 years from now).

Generally at PRA, the NPV of the stand was reduced by MPB attack. In 65 years, most of the stands had positive NPV indicating enhanced stand value. However, this needs to be compared with the NPV of clearing the residual stand and starting a new plantation. To date, none of the age class 2 scenarios of starting again has resulted in a better NPV than leaving the stand to develop after MPB attack. In some instances, the underplanting scenario does enhance NPV. The success of underplanting increases as competition from advanced regeneration decreases. From our work to date, it appears age class 2 stands will need to be managed on a stand by stand basis given the high variation in both attack and regeneration.

Conclusion

While there appears to be adequate regeneration, it is not uniformly distributed among stands. In some instances, the best management strategy may be to leave the stand alone even though PRA yields are reduced. The cost to increase the yield at PRA is not offset by the increased productivity – management results in a negative NPV.

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Acknowledgements

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Immediate Impacts of Partial Cutting Strategies on Stand Characteristics and Value

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This study evaluated the impacts of partial cutting on stand characteristics, product recovery, and financial return in mature black spruce and balsam fir mixed stands in Quebec. Four harvesting strategies (clearcut with advance growth protection, irregular shelterwood cutting leaving small merchantable stems, and two patterns of selection cutting) were each applied four times in 20 ha harvest blocks representing irregular black spruce and balsam fir mixed stands. Before the four harvesting strategies were applied, there were no significant differences in stand characteristics (i.e., quadratic mean DBH, basal area, and merchantable stem volume) or expected product recoveries (i.e., lumber volume and value, chip volume and value, and total product recovery) estimated using the Optitek

sawing simulation package. There was no significant difference in stand characteristics or product recovery values of the harvested stems between the selection cutting approaches ($p>0.05$). However, significant differences in stand characteristics and product recovery values of the harvested stems existed between these treatments and both of the two other treatments. After cutting, the two selection cutting treatments had the lowest impacts on stand characteristics, as compared to the two other treatments. The selection cutting approach which used temporary skidding trails and where cutting was initially concentrated over half of the stand resulted in the highest benefit/cost ratio, relatively high net income and high total product value of residual trees.

Choice of Management Strategies of Forests in Protected Areas Based on Growth Simulator

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Introduction

From the viewpoint of the conservation of natural ecosystems, the most valuable areas in the Czech Republic are included into integrated territorial units of large-scale particularly protected areas (national parks, protected landscape areas), which are further divided into three zones according to the degree of protection and permitted human interventions with the specific regime of protection and management.

From the viewpoint of fulfilling the aim of protection the first zones of conservation of large-scale protected areas include the most valuable parts of the territory. For these parts, a regime without silvicultural measures is legislatively defined, a regime of the autonomous development of a forest ecosystem without human interventions. Considering a fact that the first zones of conservation are not usually defined as integrated landscape segments and because they were actively affected by man in not too distant period, all parts of these areas are not equally valuable from the viewpoint of conservation objectives. Thus, also in the first zones of the conservation of large-area particularly protected territories there are parts, which markedly differ from the target idea and which require the use of special management to achieve the aim of conservation. Formulation and reasons for the determination of measures mentioned above cannot result only from the synthesis of findings on the condition and development of forest stands of the region, but it is necessary a prediction of the forest development to be available using proposed measures aimed at assessing the rate of approaching the required target condition. To assess the future development of stands and evaluate potential impacts of management measures growth simulators are increasingly used at present (eg. Pretzsch 1992, 2002, Sterba 1995, Hasenauer 1994, Nagel 1996 etc.).

A Procedure of Deriving the Management Strategy

A basic condition to derive the suitable strategy of management is the selection of an exemplary region fulfilling the target idea in all required attributes and its integrated biometrical analysis and the simulation

of development. It refers to exemplary stands (in various stages of development) and it necessary to approach their picture, species composition, texture and structure in other stands of the area using the special management strategies. Management measures are implemented in the field of silvicultural practices, selection of differentiated regeneration procedures, modification of species composition (eg., in the form of underplanting) etc. Particular measures are always proposed for a specific time step with an intensity related to particular stand components in spatial frames. At the realization and other evaluations (simulation of development) of particular measures particularly following stand attributes are monitored:

- proportion of species in particular stand components;
- number of trees of particular species in stand components;
- structure a texture (structure and texture indices, e.g. Pretzsch 2002);
- special stand quantities (particularly crown parameters, crown closure, the level of shelter, suitability of stand segments for the development of natural regeneration, the proportion of lying tree volume etc.).

Weights are attached to particular attributes (scale 1-5) to assess their significance. The rate of approaching the required target condition (convergence, divergence) is evaluated on the basis of comparing the time series of simulations (with an interval of 5 – 10 years) using Spearman's correlation coefficient. (orig. software ADOLT 2005, unpublished). The efficiency of our technology of implementation (rate of limits and hazards) is calculated by a special method (Simon, Vacek, Buček, 2004).

Using the Method of Deriving the Management Strategy on the Basis of Growth Simulations

To present the proposed methodical procedure the area of the Jelení bučina National Nature Reserve (NNR) and the adjacent part of the first zone of protection with stands with markedly changed species composition was selected as a core natural area

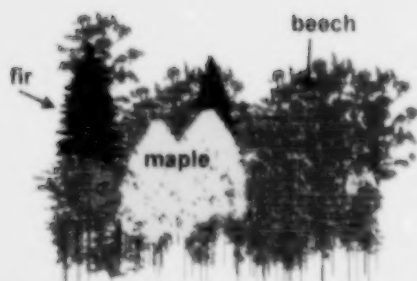


Figure 1. A stand with natural composition.

without interventions of man. The Jelení bučina NNR is situated in the Hrubý Jeseník Mts. at the northern border of the Czech Republic.

Natural composition of stands corresponding to the actual objective of protection/conservation: European beech (50%), silver fir (30%) and sycamore maple (20%). A selected stand of the Jelení bučina NNR roughly corresponds to the stand composition (Figure 1). The stand is created by an autochthonous mixed stand where self-regulation processes occur in sufficient rate. On the other hand, in allochthonous spruce stands of the remaining part of the area (Figure 2), it is necessary to use specific special-purpose management. Its objective is the gradual conversion of more or less pure and even-aged spruce stands to differentiated (in terms of species and age) stands approaching the natural composition of stands presented there as stands dominated by beech (minimum proportion 60%) in a mixture with silver fir and sycamore maple and an admixture of spruce and larch (up to 5%).

The basic requirement is, of course, the autochthonous character of species – spruce stands are mostly allochthonous. In these stands, it is possible to use (according to the condition of stands and available time horizon in dependence on the stand age) either the clear-felling system of management with subsequent graduated planting (in stands approaching the rotation period) or, in case of need, to prepare stands and to use underplanting in groups (10 – 15 plants) in ecologically favourable parts of the stand. It is necessary to calculate the time horizon of the stand regeneration to about 40 years, in 10-year intervals with 20%, 20%, 30% and 30% intensities (the implementation of underplanting follows common principles) (Vacek, Lokvenc, Souček 1995). Nevertheless, the use of suitable game management is a basic condition for the success of underplanting.

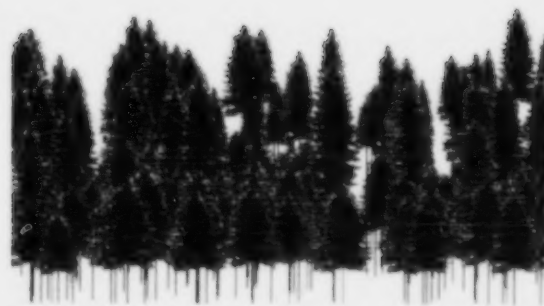


Figure 2. An allochthonous spruce stand.

Approaching the target condition was preliminarily tested on the basis of assessing the convergence or divergence of selected structural or textural indices

Conclusion

Exact formulation of the management strategy leading to approaching the stands of various character in differentiated conditions of the natural environment to close-to-nature forest is a rather complicated task and predictions of the effect of the management are problematic. For these reasons the use growth simulations is very suitable. Growth simulators represent an effective tool, which can serve to support decision making and the selection of an optimum variant on a stochastic basis. Simulations as such do not deal with the whole problem but provide supporting arguments as one of components of the process of decision making of a forest owner.

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Complexity in Modelling Residual Tolerant Hardwood Stem and Stand Growth Response to Silvicultural Treatment

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Introduction

In Ontario, tolerant hardwood stand are managed by selection or shelterwood silvicultural systems resulting in complex multi-storied or uneven-aged or two-aged stands. These systems require more complex growth and yield models to better represent their short and long-term tree and stand development trajectories. Since these systems involve multiple entries within the lifetime of a tree (most significant with the selection system) concern exists about the impact of logging damage to future crop trees and potential growth impact of compaction due to skid trails. This presentation describes the results of projects undertaken to address these concerns.

Project Overviews

Growth and Yield Modelling

Ontario's forest management planning system currently employs broad strategic level "forest unit" (FU) modelling of tolerant hardwood stand growth. Average basal area growth rates are assigned to at a forest management unit scale. Improvements to calibrating appropriate average growth rates to FU scale application of the selection and shelterwood system have been developed incorporating broad aspects of site quality, tree quality, residual stocking level and logging damage. In the simplest terms, Ontario's strategic model projects a stand level development pathway to a non-spatial landbase for the determination of allowable harvest targets and ensuring sustainability. The reality is that tolerant hardwood stands exhibit a great deal of variation in species mixture, stocking and structure.

Although tolerant hardwood management prescriptions are assigned at the stand level, the stands are managed at the tree level. That is, all tolerant hardwood stands are marked by a certified tree marker prior to any extraction with quality and size distribution targets assessed at each tree. As a result, it seemed logical to look for an individual tree model

for growth and yield prediction of these complex forest conditions. Specifically, the model needed to handle

- Mixed species
- Mixed ages and sizes
- Targeted extraction (in terms of quality and tree size distribution).

The Forest Vegetation Simulator Model (FVS) model was first tested and was then calibrated for Ontario conditions. Specific effort was placed on developing tree level models that incorporated tolerant hardwood stem quality in the model forms. Although the current model is still under development, a beta version is available from www.fvsontario.com and training sessions are planned for fall 2007. FVS^{Ontario} requires a tree list (a list of species and diameters) to initialize conditions. This has led to the development of a tree list generator software package as well as investigation of new technologies to produce more detailed inventories including size distributions.

Skid Trail Impact

In the selection silvicultural system, harvesting may occur every 15 to 30 years while in the shelterwood system, harvesting occurs two times within a rotation. Concerns were raised about the impact of repeated entries of harvesting equipment on soil structure, root development and stem growth. Preliminary results indicate soil compaction exceeds (some threshold commonly considered to be a root barrier) after as little as two to three passes (Murosky and Assan 1988, Hatchell et al. 1970) and does not revert back to natural levels through the "freeze-and-thaw" cycle as quickly as believed (Wert and Thomas 1981, Perry 1964). This has led to the consideration of recommending permanent skid trails. A study is underway to investigate the effect of skid trail proximity to tree growth. Preliminary results indicate a growth reduction in sugar maple. Further work is needed to identify whether the root barrier is more or less permanent. If the root barrier is permanent, repeated use of the skid trail may not cause further growth reductions.

Logging Damage

Repeated stand entries with the selection and shelterwood silvicultural systems increase the likelihood of damaging future crop trees. Research has looked at ways to minimize logging damage (e.g., harvesting methods, season of logging, skid trail location, operator training), examining the effect of logging damage on quality and examining the effect of damage on future growth. Research to date has focused on stem damage (Woods et al. 2007 *in press*). Additional work is needed on crown damage.

Discussion

Historically, much of the growth and yield research on tolerant hardwoods in Ontario has focused on silvicultural (tree marking) prescriptions. This has led to three important initiatives. The first is a tree marking certification program. Every tolerant hardwood tree on provincially owned land is visited by a certified tree marker prior to any harvesting. These markers consider the tree's growth potential, competition with neighbouring trees, wildlife values, recreational values, and cultural values. The second initiative is incorporation of the tolerant hardwood growth and yield research into different scale modelling efforts. The final effort has recently involved researchers studying harvesting impacts – specifically logging damage and skid trail impacts. Guidelines are in place for both of these but the link to growth and yield has been weak. This was due in part a lack of studies quantifying the impact on growth and yield and partly because of a lack of a detailed growth and yield model.

Modelling growth of tolerant hardwoods is challenging because of the mix of species, age, and sizes. These complexities are compounded by the level of detail (FU / stand level / tree level) being projected. The silvicultural systems, selection and shelterwood, raise issues of skid trail compaction and logging damage. Strategic modelling enhancements have been made through the incorporation of remeasured research and operational trials. Broad level netting down of growth rates have been applied to FU basal area growth based on stand site and stem quality, logging damage and structural targets.

Tolerant hardwood management, although managed at the stand level, are decided at the individual tree level. The interaction and issues with modelling response occurs between trees. As a result, an individual tree modelling approach was selected as the most appropriate means to model the potential

suite of responses. An evaluation of existing models elsewhere identified the FVS family of models as an appropriate for Ontario's full suite of silvicultural systems (clearcut, thinning and partial-harvesting systems). Recent work in Ontario has involved the validation and calibration of the FVS^{Ontario} (Lacerte et al. 2004), (Lacerte et al. 2006a) (Lacerte et al. 2006b). Efforts have focused on developing tolerant hardwood growth rates based on silvicultural trials throughout the Great Lakes St. Lawrence Forest Region (Woods and Penner 2007).

Whether modelled at the FU or tree level, tolerant hardwood response can be impacted by logging damage (stem, root and crown) and potentially by root shearing or compaction from skid trails. Current efforts by researchers are underway to quantify the loss of growth, quality and value due to implementing these partial harvesting systems in these forest types. Guidelines are in place for both of these but the link to growth and yield has been weak. This was due in part a lack of studies quantifying the impact on growth and yield and partly because of a lack of a detailed growth and yield model.

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Spatial Scale of Intraspecific Interference Within Commercially Thinned Jack Pine Stands and Consequences for Growth Response Modelling

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Introduction

Economic efficiency dictates that experimental commercial thinning within jack pine (*Pinus banksiana* Lamb.) stands employ a half-systematic thinning treatment where approximately 15% of the growing stock is completely harvested from a series of parallel extraction corridors followed by a selective thinning-from-below treatment within the residual leave strips. This treatment results in a pseudo-random distribution of additional growing space allocated to the potential crop trees and an overall stand structure which is spatially segregated. Although existing models, such as structural stand density management models, can be modified to account for the reduction in per unit area yields arising from systematic thinning, the nature and spatial scale of interference arising from selective thinning is unknown and hence the applicability of existing models uncertain. Conceptually, interference or competition within forest tree populations has been characterized as a continuum ranging from a resource depletion to a resource pre-emption process. The resource depletion process is characterized as a symmetrical relationship in which all competitors acquire an equal size-proportional share of the belowground resources (e.g., all competitors acquire an equal share of the available nutrients and moisture on a per-unit size basis). Conversely, the resource pre-emption process is characterized as an asymmetrical relationship in which larger-sized competitors acquire a greater size-proportional share of the aboveground resources than smaller-sized competitors (e.g., larger-sized competitors acquire a greater share of the solar-based resources than smaller-sized competitors on a per-unit size basis). Additionally, within density-stressed jack pine stands, the spatially noncontiguous nature of crown cover (crown shyness) combined with the numerous crown collisions commonly observed during wind events suggest that physical competition for aerial space, may also be an important component of intraspecific interference. Within this conceptual framework, the objective of this study was to examine the nature and spatial scale of interference within commercially-thinned jack pine stands and the associated consequences in terms of growth response modelling.

Method

Experimental Sites and Measurements

Two sets of replicate even-aged monospecific (>90% jack pine by basal area) stands situated in the transitional area between the Central Plateau (B.8) and Nipigon (B.10) Forest Sections of the Canadian Boreal Forest Region (Rowe 1972) were selected for analysis. The replicate stands within each set (denoted Stands A and B (Set 1) and Stands C and D (Set 2)) were approximately equivalent in terms of their disturbance history (fire-origin 1945 (Stands A and B); 1956 (Stands C and D)), silviculture history (precommercially thinned (1962)), structural characteristics (random spatial patterns with unstratified vertical structures and unimodal horizontal size distributions), and site characteristics (dry-moderately fresh, sandy soil jack pine conifer types). Four 0.071 ha (Set 1) or 0.062 ha (Set 2) circular sample plots were established within each stand in 2000 and following measurements obtained: outside-bark diameter at a height of 1.3 m (D ; ± 0.1 cm), total height (H ; ± 0.01 m), and polar co-ordinates (azimuth ($\pm 1^\circ$) and distance (± 1.0 cm) from the plot centre. Selective thinning treatments were randomly applied within 3 plots per stand. The treatments attempted to reduce local competition and stand-level density-stress levels by removing competitors within a 2-3 m radius of each selected crop tree. Historical tree reconstruction analysis including destructive stem analysis was completed on each of the thinned trees from which stand-specific trigonometric-based taper/volume and allometric-based aboveground mass equations were developed. Five years after treatment (2005), all surviving trees on all the 16 plots were remeasured for D and H from which relative periodic diameter and volume growth rates were calculated.

Analysis

Eight spatially-explicit local competition indices (Hegy 1974; Weiner 1984; Silander and Pacala 1985 and their spatially modified forms (Newton and Jolliffe 1998)), and 1 nonspatially-explicit index (point-density (competitors /m²)), were used to quantify the degree of local competition around each crop tree. Eight discrete competition radii (2 m to 9 m by 1 m intervals) were used to define the size of the competition neighbourhood for each index. Based on a graphical assessment of

the principal trends between the response variables (relative periodic diameter and volume growth) and each competition index by neighbourhood radius, plot and stand, 4 candidate functional forms were considered: linear; semi-logarithmic; inverse; and double-logarithmic. Results from linear correlation analysis and associated randomization tests were used to identify the most appropriate functional form between the each response variable and competition index (e.g., Eq. (1)).

$$(1) \quad RGR = b_0 + b_1 \frac{1}{CI_{HN}} + e$$

where RGR is relative periodic volume growth rate, CI_{HN} is a spatially-modified formulation of Hegyi's (1974) index (Eq. (2)), and are intercept and slope parameters (estimated by ordinary least squares regression analysis), respectively, and e is an error term.

$$(2) \quad CI_{HN} = \left[\sum_{m=1}^M (TM_m / TM_c) / R_c^2 \right] \left[1 - (R_{CM} / R_{MSW}) \right]$$

where and is the total mass (g) of the m th competitor ($m = 1, \dots, M$; M = total number of competitors within a crop tree's neighbourhood), TM_c is the total mass of the crop tree estimated employing the stand-specific allometric prediction equations, is the linear distance (m) between the crop tree's spatial position and the spatial position of the m th competitor, is the radius (m) of the competition neighbourhood assessed (2 m to 9 m by 1 m intervals), and is the linear distance (m) between the spatial position of the crop tree and the spatial position of the competitors' centre-of-mass. The spatial modifier attempts to account for spatial heterogeneity among competitors (see Newton and Jolliffe 1998).

Graphical analysis was used to examine the influence of spatial scale on the competition relationships within the jack pine stands via the collective assessment of the pattern of change in the sample-based product-moment correlation coefficient (r_s) as the competition radius increased. The significance of the linear association between each response variable and competition index was assessed employing randomization tests given the possibility that some of the observations may not have been statistically independent: crop trees may have been classified as competitors and visa versa (Sokal and Rohlf 1981; Mitchell-Olds 1987). Specifically, a null distribution of 1000 product-moment correlation coefficients (r_o) for each relationship was generated by randomly allocating competition index values to each

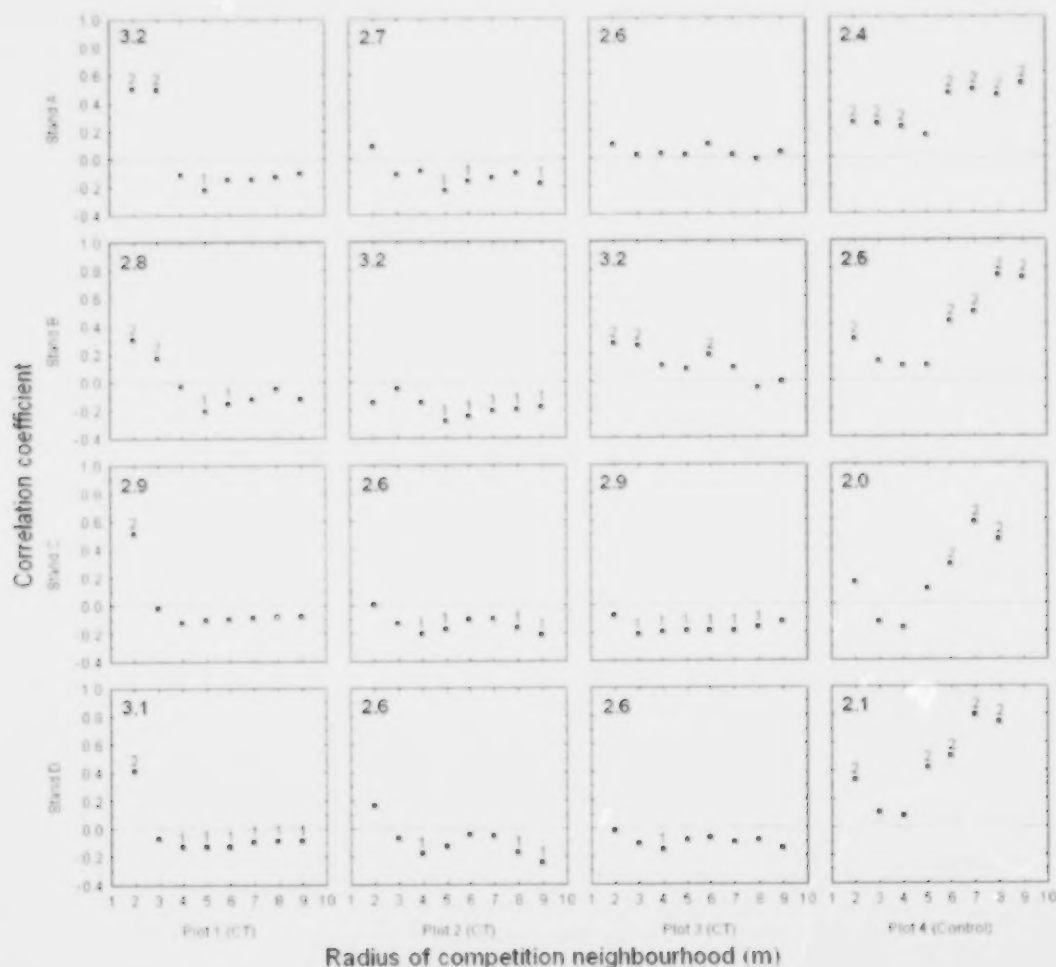
crop tree within each plot. The r_s was subsequently compared to this null distribution to determine the percentage (P_r) of r_o 's (1) less than or equal to r_s if $r_s < 0$, or (2) equal to or greater than r_s if $r_s > 0$. Note, P_r is a non-parametric estimate of the significance level for a given relationship within each plot.

Results

The following figure graphically illustrates the linear correlation for the $RGR - 1/CI_{HN}$ relationship (Eq. (1)) at each spatial scale by plot (treatment) and stand. Significant ($p \leq 0.10$) relationships are denoted by the numerals 1 and 2: specifically, 1 indicates a directly proportional or positive relationship between RGR and CI_{HN} whereas 2 denotes an inversely proportional relationship or negative relationship between RGR and CI_{HN} . The nominal spacing (m) within each plot at the time of treatment is shown in the upper left-hand side of each subgraph. Within the control plots, negative interference was detected at two distinct spatial scales (i.e., approximately 2 m and 7 m). Within the selectively thinned plots, negative interference was detected at the smaller spatial scales (2-3 m) in 42% of the plots whereas positive interference was detected at the larger spatial scales (3-9 m) in 75% of the plots. Although similar patterns were observed for the other relationships, Eq. (1) was considered the best among the 72 relationships evaluated (4 model specifications x 9 competition indices x 2 response variables).

Discussion

The results of this study indicated that interference effects were negative and operated at both a small (2-3 m) and large (5-9 m) spatial scale within fully-stocked semi-mature jack pine stands. Plausibly, at the small scale, interference may be due to frictional interactions among crowns (asymmetrical process) whereas at the larger scale, interference may be due to competition for belowground resources (symmetrical process). The relationships for the treated stands suggest that thinning mitigated the large scale negative interference effect, possibly via the increased availability of belowground resources. However, thinning did not entirely eliminate the small scale negative interference effect in all plots. Analysis of the height/diameter ratios at the time of thinning indicated that many trees were structurally unstable (mean ratio of 1.17 (min/max = 1.10/1.28) for treated plots and 1.22 (min/max = 1.18/1.28) for the control plots). Consequently, as the stands were opened up via thinning, crown sway distances and associated collision forces would increase; thus providing the



potential for continued collisions and associated losses of foliar biomass resulting in growth rate declines. The underlying mechanism for the large scale positive effect within the thinned stands is unknown. However, the damping effect of the population in dissipating wind energy (reduction in the force of the collisions) combined with the greater inter-tree distances (reduction in the frequency of collisions), may be involved. In summary, the spatial scale of interference and the possible role of asymmetric competition for aerial space suggest that spatially-explicit individual tree-level models with inclusion of small and large scale effects expressed via variable-size competition indices may be applicable when attempting to quantify growth responses of commercially-thinned jack pine stands.

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Effects of Stand Structure on Regeneration Dynamics of Mixed Uneven-Aged Forest

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Introduction

Uneven-aged fir and beech forests today are usually characterized by disturbed and frequently unstable uneven-aged structure. Some of the problems in managing such stands, as well as causes of disturbances, are: absence of natural fir regeneration, large shifts from optimal stand volume, volume increment decrease, physiological weakening and die-back of dominant trees, negative impacts of climate change (warming, drought and acid rain). Diverse impacts of these disturbances are especially important in the protected areas (such as national parks), and data from the monitoring of the changes in forest structure and the effects on the natural forest regeneration are essential for the decisions that have to be made about the future of these areas.

The goal of this paper is to present some of the results from almost a decade long (9 years) monitoring of regeneration dynamics in the uneven-aged mixed forest of fir (*Abies alba* Mill.) and beech (*Fagus sylvatica* L.) typical for the major part of the beech-fir forests in the Dinaric region of Croatia (Dubravac et. al. 2007). The monitoring was performed on the permanent experimental plot in the National Park 'Risnjak'. This National Park was established in 1953, and since then no management activities were performed.

Material and Methods

In 1998 a permanent experimental plot 100 x 100 m in size was set up in National Park 'Risnjak'. Plot is situated on dolomite parent rock with luvisol and cambisol soil types in the lower part of the plot, and rendsic leptosol in the higher portion of the plot. All trees over 8 cm in diameter at breast height (DBH) were stem-mapped, numbered and measured for DBH. Stand structure was measured in detail on a subplot 60 x 60 m in size (Figure 1) in 1998 and remeasured in 2007. All marked trees on the subplot were measured for total height and height to crown base, and detailed map of crown projections was made. Terrain height at the position of each mapped tree on the subplot was measured with Laser Vertex L400 (Haglof, Sweden) as a height difference in relation to the point with known height above sea level. Total terrain height difference between the lowest and highest point on the subplot amounts to 15 m (680 – 695 m a.s.l.). Obtained terrain heights were interpolated in ESRI's ArcMap and three-dimensional digital model of terrain relief was created. Maps of gaps and canopy cover by tree species and by canopy layers were produced from the map of crown projections. Regeneration dynamics was monitored in 1998, 2001, 2003 and 2007 on three strips within the subplot, each 120 m² in size (2 x 60 m). All plants

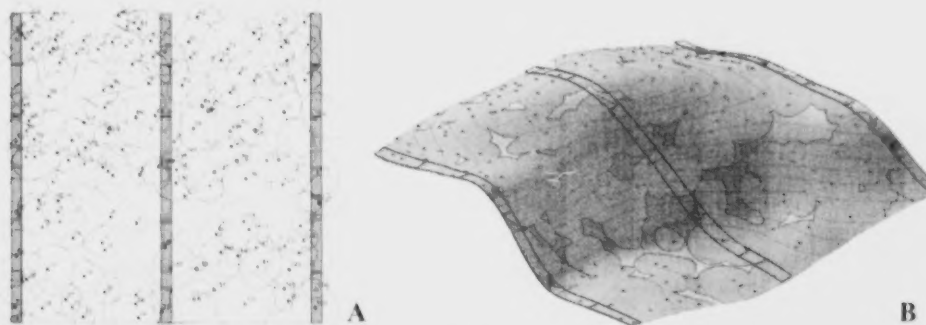


Figure 1. Subplot 60 x 60 m in size: A – layout with position of trees, crown projection areas and three strips on which the regeneration was monitored; B – three-dimensional terrain relief of the experimental plot.

on these strips were tallied according to their life form (tree or shrub), species, age (one-year old or older) and height. In 2007 each of these three strips was further subdivided in six 2 x 10 m sub strips. Percent of canopy cover, percent of canopy cover by fir, percent of canopy cover by beech and average slope were calculated for each of 18 sub strips.

Results

The diameter distribution of fir and beech has not changed dramatically within the monitoring period. Fir is still practically non-existent in smaller diameter classes, which indicates very poor fir recruitment during the last few decades. Instead of fir, young beech plants are filling in the lower diameter classes.

The number of fir plants in understory is steadily decreasing during last nine years, and not one fir plant grew over 30 cm in height. The share of beech in the total number of understory plants has increased from 16.1% in 1998, up to 58.3% in 2007. Beech plants in the understory community are of low quality, especially stem-wise, but they are gaining in height and pretend to take position in the canopy strata of the forest stand.

Total number of plants on forest floor counted in 2007 on 18 small plots showed no correlation with percent of the canopy cover and showed negative correlation with slope, except for two plots on steep slope with exceptionally great number of beech plants, probably because of the debris (dead branches) that stopped heavier beech seeds from rolling down. There was no correlation between the emergence of fir seedlings and the percent of canopy cover by fir trees. We found a strong negative correlation between percentage of freshly emerged fir seedlings and percentage of beech plants, but no correlation between the share of older firs and percentage of beech plants in the total number of understory plants.

Discussion

Understory plant community greatly influences microclimatic conditions on the forest floor (Bartemucci et al. 2006) that are important for successful emergence of young plants and are crucial during the first few years of their life. With regard to the species composition of the understory community, it is evident that fir seedlings emerge on spaces with low percentage of beech plants. Lack of transition of fir regeneration from seedling to sapling stage is evident in the investigated stand, since none of the young fir plants grew over 30 cm in height during nine years. Because of plasticity of its canopy growth, beech will

continue to fill the spaces in the vertical structure and further deteriorate microclimatic conditions on the forest floor.

These results offer grim perspective on future of the investigated stand. As old fir trees die, the source of fir seed will diminish, and the seed that gets to the floor will end up in beech dominated environment. This would ultimately lead to the species substitution as already noticed in nearby Slovenian beech and fir forests (Bončina et al. 2003). Species substitution is even more concerning since it is underway in the forests of the National Park of which uneven-aged fir and beech forests are the main feature. We must ask ourselves: Should we protect the natural processes such as species substitution and prohibit human intervention, or should we protect the forests that are a product of these processes?

Conclusions

During the nine years of monitoring we recorded a decrease in the number of young fir plants and a lack of transition of fir plants from seedling to sapling stage, since none of the young fir plants grew over 30 cm in height during the last nine years. The share of beech in the total number of understory plants has increased from 16.1% in 1998, up to 58.3% in 2007. Fir is non-existent in lower classes of diameter distribution, which indicates very poor fir recruitment during the last few decades. Natural regeneration of shade-tolerant fir, as a basic condition of the structural stability of these stands is questionable. Therefore, the monitoring of these and other processes should be continued and further developed, and the data obtained should be utilized through stand simulators to produce several scenarios as a basis for the decisions that have to be made about the future of these stands and the National Park 'Risnjak' itself.

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Understory Development and Stand Succession Study in Alberta

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Introduction

An in-depth understanding of stand dynamics and succession is required for ecosystem-based forest management, however, this information is typically not available at the landscape level. Boreal mixedwood stands do not converge to a single climax forest community but take different paths due to short historic fire cycles, availability of seed sources, site conditions, and silvicultural treatments. Through gap dynamics and self-recruitment, aspen can dominate a site for an extended period of time (Cumming *et al.* 2000). Understory white spruce recruitment may occur at the same time under an aspen canopy (Lieffers *et al.* 1996, Peters *et al.* 2006). Using multiple layers of forest inventory, this study analyzed understory development and landscape level succession trends in the Boreal Forests of Alberta, Canada.

Data and Methods

Forest inventory data, containing 470,104 stands from north-east Alberta, was used to study understory development. In the succession study, 25 samples were randomly selected after removing areas of major water bodies, transportation corridors, or recently disturbed by fire or harvesting. Each sample represented a quarter of a township with an area of about 2,500 ha. The aerial photo coverages from 1950, 1970 and 1990 were selected. Based on the 1990's inventory data, old photographs were interpreted to the current standard with a digital stereophotographic technology which allows for accurate identification of changes in vegetation cover over time. Changes in stand conditions, such

as species composition, density and understory occurrence, were investigated between any two sequential classifications. Stands of pure white spruce (Sw), white spruce- (SwAw) or aspen-leading (AwSw) mixedwoods, pure aspen (Aw), and pure aspen stands with understory (Aw/Sw) were of primary interest. The percentage that a cover type was reclassified into another cover type (succession transition) was analyzed by age group and time lapse period. Statistical tests of density and succession changes were conducted with SAS®.

Results

The occurrence and composition of understory are related to overstory cover type, age and density. Many aspen stands do not develop understory. In mature and old classes, only 16.1 and 28.7% of the stands have understory, respectively. Most (55-70%) of the interpreted understory types are pure white spruce (Table 1) and the majority Aw/Sw stands are "C" or "D" density (50 to 72% and 5 to 28%, respectively). In comparison, stands with aspen understory are mainly open stand types: over 50% of stands are "A" density and 30-40% as "B" density.

Under a pure aspen overstory (Figure 1), understories appear to have developed 0-30 years after the overstory; with fewer stands exhibiting longer lag times. Aspen understories are more common than other understory types in the 50- to 90-year lag period, suggesting that an understory aspen layer may replace the overstory aspen in 40 to 60 years when the overstory dies out at about 120 years of age.

Table 1. Understory distribution in stands with understory for four overstory cover types with number of stands (N) and their contribution to the total each row (%).

Age Group	Overstory Type	Aw		AwSw		SwAw		Sw	
		N	%	N	%	N	%	N	%
Mature (61 - 110 years)	Aw	2,031	9.6	283	1.3	233	1.1	15,005	70.7
	AwSw	170	9.1	69	3.7	54	2.9	725	39.0
	SwAw	97	17.2	23	4.1	18	3.2	101	17.9
	Sw	265	21.3	51	4.1	47	3.8	218	17.5
Old (111+ years)	Aw	1,756	32.1	189	3.5	95	1.7	2,944	53.8
	AwSw	279	21.8	88	6.9	49	3.8	567	44.2
	SwAw	256	20.6	101	8.1	100	8.1	431	34.7
	Sw	779	18.1	245	5.7	176	4.1	1,707	39.8

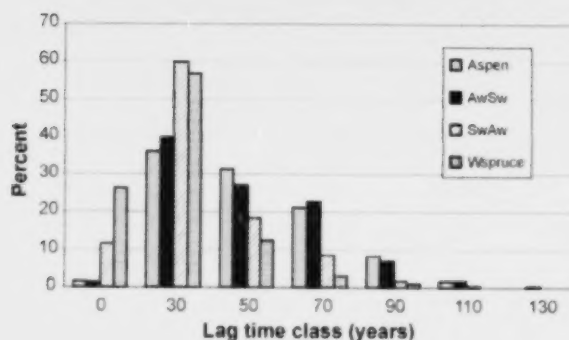


Figure 1. Distribution of lag time by stand count of different understory types under pure deciduous canopy.

Significant levels of succession changes are observed in mixedwood stands, with the general trend from pure deciduous to deciduous with understory, then to mixedwood, and to white spruce (Table 2). A pure deciduous stand has a 14 to 21% chance of transitioning to another stratum. The transition from mixedwood to pure white spruce is significantly greater than zero ($\alpha=0.05$). Changes of cover types over a 40-year lapse period are higher than those over a 20-year period.

Discussion

Only about 16% of aspen and aspen-leading mixedwood stands have understory. Extensive aspen dominance may occur because of poor coniferous understory development or substantial aspen regeneration (Table 1) in the gaps or below break (Cumming *et al.* 2000). Mature age pure aspen stands make up over 70 percent of all stands developing understory and most understories are white spruce dominant. The majority of white spruce understories

develop less than 20 years (prior to canopy closure) while another peak occurs over 30 years (Figure 1). This data are consistent with the findings of Peters *et al.* (2006).

The patterns of succession in Alberta differ from results from similar projects in Ontario (Ride *et al.* 2001) and Saskatchewan (Liu *et al.* 2005). Succession in Alberta is occurring more slowly than in Saskatchewan and Ontario (Ride *et al.* 2001) and Saskatchewan (Liu *et al.* 2005). Succession in Alberta is occurring more slowly than in Saskatchewan and Ontario.

For example, 65, 34 and 17% of studied aspen stands transitioned to other types in Ontario, Saskatchewan, and Alberta, respectively. This pattern of decreasing successional transition is mirrored by an increasing seasonal fire risk from east to west.

Frequent disturbance and drier climate may result in slower succession in the Albertan Boreal Forest Natural Region, compared to other study sites of the boreal forest.

Conclusion

Different types of understory occur across the landbase but the majority of deciduous stands do not have any understory development. Compared to similar studies in other parts of the boreal forest, succession changes in the Albertan boreal forest are slower which could be related to landform, climate, and seasonal forest fires severity. Frequent returns of severe wildfire disturbance, drier climate and flat landforms have favored the development and maintenance of deciduous stands but do not favor coniferous understory or coniferous stands in Alberta.

Table 2. Changes from current cover type (columns) to futures cover types. Chi-square test is for the significance of one cover type's distributions between two periods of lapse.

Lapse (year)	Cover Type	Aw %	Aw SE	Aw/Sw %	Aw/Sw SE	AwSw %	AwSw SE	SwAw %	SwAw SE	Sw %	Sw SE	Chi square test	
		%		%		%		%		%		p value	Prob> p
20	Aw	85.9 ^a	3	10.0	2.7	2.7	1.1	0.4	0.2	0.2	0.1	2.4E-14	6.9E-12
	Aw/Sw	15.6 ^a	6.8	79.1 ^a	3.7	2.7	2.4	0.7	0.7	1.9	1.2	0.080	0.371
	AwSw	8.7 ^a	2.5	0.4	0.3	79.9 ^a	3.7	5.5 ^a	2.2	0.9	0.4	4.1E-05	1.9E-03
	SwAw	3.5	1.9			0.7	0.3	75.0 ^a	4.6	7.9 ^a	2.2	2.3E-03	0.069
	Sw	2.6 ^a	1	0.7	0.5	0.4	0.3	3.7 ^a	1.3	89.5 ^a	2.7		
40	Aw	79.3 ^a	4	16.2 ^a	3.7	2.4 ^a	1.1	0.3 ^a	0.1	0.3 ^a	0.1	numbers labeled with letters are different from zero	
	Aw/Sw	11.5	6.3	83.5 ^a	1	1.0	1			4.0	3		
	AwSw	9.6 ^a	3.5	0.4	0.2	67.5 ^a	4.6	6.1 ^a	2.4	5.8	3.8		
	SwAw	6.7 ^a	2.4	1.5	0.9	0.2	0.2	67.8 ^a	5.9	7.0 ^a	2.3		
	Sw	4.5 ^a	1.8	0.8	0.4	0.2	0.2	2.1	1.2	89.7 ^a	3		

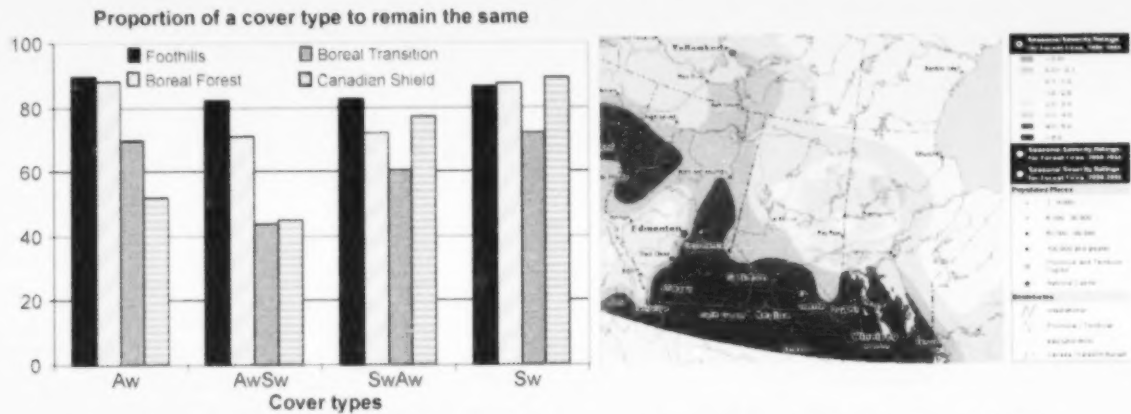


Figure 2. Comparisons of changes of four stand cover types over 20 years of time (left) of four study areas, spatially shown with seasonal forest fire severity rating for 1980-1989 (right).

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Annual Variation in Growth and Stand Dynamics in Jack Pine Forests: Insights From Tree-Ring Reconstruction

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Introduction

We used tree rings to reconstruct the growth and stand dynamics of jack pine forests in Saskatchewan and Manitoba, Canada. Presently, such dynamics are monitored using periodic re-measurement of permanent sample plots (PSPs). In our study, many aspects of forest growth and stand dynamics, including growth increment, mortality, competitive symmetry, size distribution, size inequality, and spatial autocorrelation, show striking patterns of annual variation. These patterns would not be as evident in periodically collected data.

Materials and Methods

We sampled ten plots in five regions along a north-south gradient of decreasing precipitation and increasing temperature, located near (i) Prince Albert, SK, (ii) Candle Lake, SK, (iii) Flin Flon, MB, (iv) Jenpeg, MB, and (v) Thompson, MB. At each plot (100m² or 900m² depending upon region) we measured heights and diameters, and mapped stems at 900 m² plots. We extracted two randomly oriented increment cores at breast height for living trees and a cross-sectional disc for dead trees. We measured ring-widths on these samples using WinDendro, and

so conducted a full census of all living trees, standing snags, and downed logs present in the stand at the time of sampling. We used diameters reconstructed from tree-rings and allometric equations to reconstruct the volume growth of each tree in our plots and found this to be accurate relative to error accepted in other mensurational studies. Based upon when we observed mortality occurring relative to when mortality would be expected to occur from self-thinning and our estimates of how long downed logs had been on the ground relative to how quickly they are expected to decompose, we believe we can reliably reconstruct these plots 50 years into the past.

Results

In this summary, we present only a few of the growth and stand development trajectories that it is possible to examine with these data. Figure 1 plots annual change in the spatial relationships of tree locations, tree sizes, and size increment of a 900 m² plot located at Candle Lake since 1950, based on point pattern analysis techniques (Ripley's K and mark correlation functions (Fortin and Dale 2005)). The spatial pattern of tree locations at the plot is random at all distances up to 10 metres. There is negative autocorrelation in tree size and size increment at a distance of

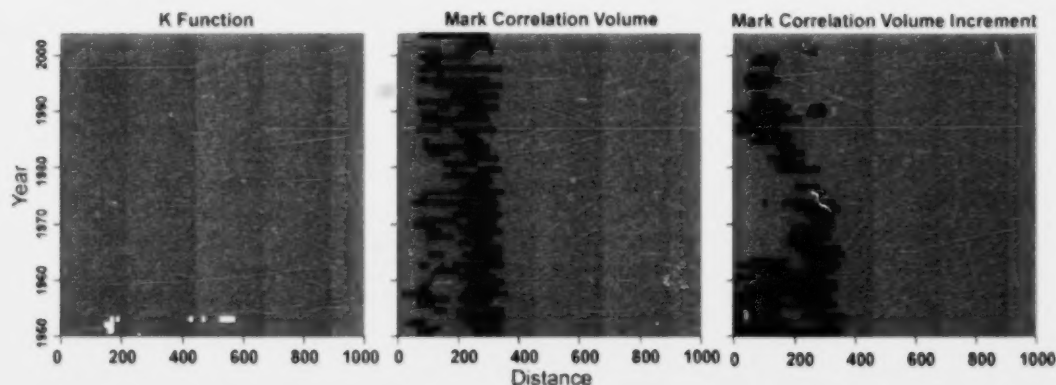


Figure 1. Temporal changes in the spatial distribution of tree location, size, and size increment at a 900m² jack pine plot at Candle Lake, SK, since 1950. Gray areas indicate random distributions (no autocorrelation) black areas regular distributions (negative autocorrelation) and white areas clumped distributions (positive autocorrelation).

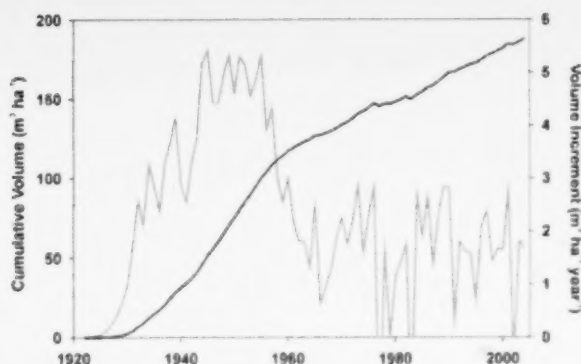


Figure 2. Net cumulative and incremental volume growth of a 900 m² jack pine plot at Candle Lake, SK reconstructed from tree-ring samples taken in 2005.

about 3 metres, but this is highly variable. In some years, size increment shows no autocorrelation at all. Our methods can also retrospectively obtain the data normally acquired by periodically permanent sample plot (PSP) measurements. Figure 2 plots the cumulative and incremental net volume growth of the same plot at Candle Lake. Figure 3 plots the spatial distribution of live and dead trees at this plot every 10 years since 1960. These data were obtained from samples collected in 2005, and did not require a PSP to have been established at this site 45 years ago.

Discussion and Conclusion

Annual resolution data would allow forest growth and stand dynamics models to more easily investigate and account for transient factors like insect defoliation and drought that influence these processes at an annual scale. This would be particularly important if

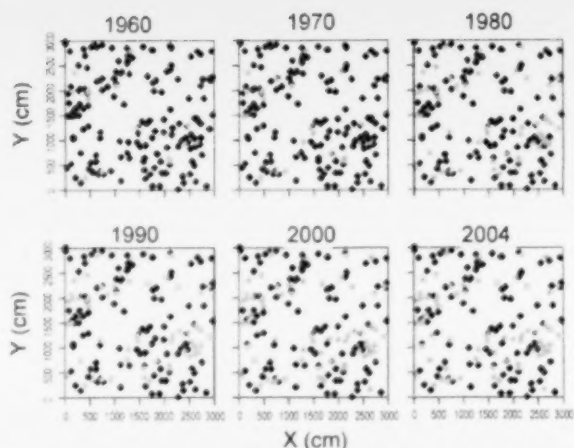


Figure 3. Changes in the spatial distribution of live (black) and dead (grey) trees at a 900m² jack pine plot at Candle Lake, SK, reconstructed from tree-ring samples taken in 2005.

they wish to assess the effects of transient factors like insect defoliation or drought on forest growth (e.g. Hogg et al. 2005, Hogg and Wein 2005) or competition processes (e.g. Wichmann 2001). We are presently using the data that we collected from these reconstructions to explore these dynamics.

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Coarse Woody Debris Dynamics in the Boreal Forest of Central Canada: Influence of Fire, Forest Composition, and Forest Management on Structural Diversity

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Introduction

Central to sustainable forest management in the boreal forest is maintenance of coarse woody debris (CWD) as it regulates wildlife habitat^{1,16}, water, carbon, and nutrients^{10,21}, and forest regeneration^{11,18}. Although the importance of CWD has been well documented, the effect of time, forest composition, and forest management on various CWD characteristics, including volume, composition, and size-variability, is still poorly understood. The quantification of stand structural attributes using diversity indices is a relatively new concept in forestry¹⁷. We conjecture that CWD size-variability should increase with stand development, as successional trajectories result in the replacement of pioneering tree species with later successional tree species that have different growth potentials and attributes than their predecessors³. Furthermore, we hypothesize that CWD species-variability should increase with stand development, a consequence of the replacement of pioneering tree species with later successional tree species that result in increased live tree and therefore CWD species richness. We also theorize that CWD decay-variability should follow an inverse U-shaped pattern with stand development, where decay-variability is low shortly after fire when CWD is relatively undecayed, higher later in stand development when pre-disturbance CWD has significantly decayed and longevity-related mortality begins inputting CWD in early states of decay, and low late in stand development when pre-disturbance CWD has largely disappeared and inputs from the breakdown of the pioneering cohort show little decay.

Stand overstory tree species composition may affect CWD characteristics as it influences forest productivity^{4,9,13,14}, stand structure of live trees^{2,20}, and understory plant biodiversity⁸. Mixed-species stands may contain greater CWD size-, species-, and decay-variability, a consequence of inherent differential tree life history traits^{5,9,13,14}, higher tree species richness and contrasting conifer and broadleaf decay rates^{6,22}. Clearcut logging is applied in the boreal forest with the intent that it, to some extent, emulates wildfires¹⁵. Logging removes trees for commercial usage, leaving small amounts of logging slash and undesirable tree species on the ground and a few residual trees and snags, highlighting that postlogged stands are missing a large

pre-disturbance input of CWD. However, we hypothesize that CWD structure in postfire and postlogged stands may converge later in stand development once pre-disturbance CWD commences decaying.

Materials and Methods

The study was conducted in the boreal forest north of Lake Superior and west of Lake Nipigon approximately 150 km north of Thunder Bay, Ontario. We sampled 54 fire-origin and 18 logging-origin stands that ranged in age from 7 to 201 and 7 to 31 yrs, respectively. For each mode of stand origin, three stand types were sampled: conifer, broadleaf, and mixedwood. With the exception of 7-yr-old stands, stand type classification depended on the basal area of conifer and broadleaf tree species of all trees ≥ 2 cm in DBH (diameter at breast-height). Broadleaf and conifer stands had an overstory of $\geq 75\%$ broadleaf or conifer species, respectively, while mixedwoods had conifer and broadleaf species in relatively equal proportions. Trees in 7-yr-old stands were not yet 2 cm DBH, so stem density and pre-disturbance overstory composition were used for classification.

Within each stand, a 400 m² circular plot was established. Within the plot, the DBH, height, and species of all snags (DBH ≥ 2 cm, height ≥ 2 m, $<45^\circ$ vertical lean, and no living foliage¹²) were measured. The line-intercept method was used to sample downed woody debris (DWD)¹⁹. The intercept-diameter (≥ 2 cm), midpoint-diameter, length, species, and decay class of all DWD that intersected the transects were measured. Morphological characteristics were used to identify DWD to species. Quantification of snag-size and -species diversity was performed using Shannon's index (H')¹⁷. DWD-size, -species, and -decay diversity were calculated for intercept-diameter, midpoint-diameter, length, species, and decay class using H' . Since we were missing older logged stands, we conducted analysis in two steps. We first determined if snag and DWD species, size, and decay (DWD only) diversity differed in 7- to 201-yr-old fire-origin stands by time since fire (TSF) and stand type. Second, we examined if the same variables differed with time since disturbance (TSD), stand type, and stand origin between 7- to 25-yr-old fire-origin and 7- to 31-yr-old logged stands.

Results

Snag and DWD species-based H' differed with TSF and stand type, increasing from 25 to 124-139 yrs. Species diversity either increased or remained unchanged from 124-139 to 201 yrs since fire depending on stand type and index. Among stand types, mixedwoods had the highest snag and DWD species-based H' in all TSF classes except for 201 yr-old stands where conifer was highest. Snag and DWD size- and DWD decay-based H' differed with TSF but not stand type. Snag size-based H' increased from 7 to 25 yrs, decreased from 25 to 72-90 yrs, increased from 72-90 to 124-139 yrs, and decreased from 124-139 to 201 yrs since fire. DWD size-based H' decreased from 7 to 25 yrs, increased from 25 to 72-90 yrs, decreased from 72-90 to 124-139 yrs, and increased from 124-139 to 201 yrs since fire. DWD decay-based H' increased from 7 to 72-90 yrs then decreased from 72-90 to 201 yrs since fire.

Snag and DWD species-based H' differed with TSD, stand type, and origin. For all stand types, there was a greater proportion of *Betula papyrifera* snags and DWD in logged compared to fire-origin stands. Snag and DWD size-based H' differed with TSD and stand origin but not type. Snag size diversity was substantially greater in 7 yr-old fire-origin compared to 7 yr-old logged and 25-31 yr-old fire- and logging-origin stands. DWD size diversity was generally greater in fire- than logging-origin stands. DWD decay-based H' differed significantly with TSD but not stand type or origin, where 25-31 yr-old stands were more diverse than 7 yr-old stands.

Discussion

Species replacement patterns for CWD proceeded through stand development from a greater proportion of early successional species to a greater proportion of later successional species and reflected canopy succession², causing CWD species diversity to generally increase from 25 to 124-139 yrs, as inputs of later successional CWD gradually joined the early successional CWD pool, which persisted well beyond over-maturity. The pattern of DWD decay diversity with TSF followed an inverse U-shaped pattern with stand development, increasing from 7 to 72-90 yrs and decreasing from 72-90 to 124-139 yrs. DWD decay diversity increased after fire as pre-disturbance DWD began to decay, while self-thinning- and longevity-related mortality produced DWD in early states of decay. Beyond stand maturity, most pre-disturbance and self-thinning generated DWD had decayed reducing DWD decay diversity. The temporal changes in CWD size-variability in this study are more

complicated than the largely linear increase with stand development reported Harper et al.⁷, where single-tree replacement is prominent and structural development often occurs without species replacement. A more abrupt canopy turnover and change in dominating tree species resulted in different canopy structural change with stand development². Mixedwoods generally contained greater CWD species diversity compared to conifer and broadleaf stands as CWD inputs were from a greater number of tree species. CWD in mixedwoods appear to be no more variable in size or decay than conifer or broadleaf stands.

The CWD dynamics in the stands we studied differed greatly between stand-replacing disturbance mechanisms, and it is evident that by approximately 30 yrs after fire or logging, not enough time had elapsed for CWD convergence to occur. Logged stands notably contained a greater proportion of *Betula papyrifera* snags and DWD than postfire stands. Leaving a greater proportion of conifer snags may provide increased habitat opportunities for birds and subnivean-dwelling mammals that rely on snags and DWD.

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Modelling the Development of Complex Stand Structure With SORTIE

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Introduction

Complex stand structure is important to numerous elements of the forest biota associated with late-successional stands. In the absence of disturbance, autogenic processes such as canopy tree senescence, understory release, canopy differentiation, and decomposition of standing and downed dead trees, give rise to an array of structurally complex habitat features over time (Franklin et al. 2002, Brassard and Chen 2006). The rate at which these complex features arise determines a stand's stage of structural development, and its capacity to support different biological communities as it ages.

Individual-based models of stand dynamics are valuable tools for projecting the development of complex stand structure (Groot et al. 2004). We used one such model, SORTIE, to examine the structural dynamics of an eastern boreal mixedwood stand, and to identify the timeframes at which the simulated stand exhibited pronounced changes corresponding to different stages of development.

Methods

SORTIE is a spatially explicit, individual-based model of stand dynamics (Coates et al. 2003). The version we use here was parameterized for mixedwood stands in the boreal claybelt region of northeastern Ontario and western Quebec (approximately 49° N, 79° W). Currently, model parameters are still at a testing stage and all results we present are considered preliminary.

The initial conditions in our simulation consisted of a 2.6 ha stand with 1500 1-cm diameter stems per hectare each of trembling aspen (*Populus tremuloides*), balsam fir (*Abies balsamea*), and white spruce (*Picea glauca*). We ran the model for 50 5-year timesteps, giving a simulation period of 250 years. At the end of each timestep, we described the stand's condition by calculating values for one compositional variable and nine structural variables. We performed a principal components analysis (PCA) on the structural attribute values from each timestep to find simulation years marking sharp changes in stand developmental patterns.

Results

Changes in stand composition and structure over the simulation period are illustrated in Fig. 1. A PCA (not shown) revealed four distinct periods of development during which structural attributes varied in a roughly linear fashion. During the first 45 years of the simulation, several structural variables fluctuated strongly as the canopy closed and self-thinning produced a high density of snags. Years 50-125 represented a period of stand maturation marked by mixed composition, increasing tree diameter diversity, foliage height diversity, horizontal heterogeneity, and wood debris cover, and decreasing snag density. Years 130-195 marked a period of transition during which the aspen cohort was lost, large spruce density increased, trees became more uniformly spaced, and gaps emerged from the loss of aspen and spruce canopy trees. The final 55 years of the simulation could be considered a steady-state phase during which the stand was uneven-aged and comprised of balsam fir regenerating under its own shade. Gap frequency decreased sharply, but diameter diversity, horizontal heterogeneity, tree spacing, and woody debris cover either reached or remained close to their peak values.

The stages of stand development identified in the simulation correspond reasonably well with conceptual models (e.g., Bormann and Likens 1979, Oliver and Larson 1996, Franklin et al. 2002). Over a 250-year period, structural changes defined periods of self-thinning, maturation, transition, and self-replacement. These periods also reflected changes from shade-intolerant to shade-tolerant species composition, and from an even to an uneven age-class structure.

Our simulation lends some insights into the importance of disturbance in boreal mixedwood stands. In the absence of disturbance, shade-tolerant balsam fir was perpetuated in single-tree canopy gaps arising from senescence mortality. The resulting self-replacing pure balsam-fir stand would not often be found in this region, however. Spruce budworm (*Choristoneura fumiferana*) prevents long-term balsam fir dominance by periodically killing off mature balsam fir trees, and wind acts to create larger canopy gaps that maintain species with lower shade tolerance. The importance of these processes could be investigated by incorporating secondary disturbances into future SORTIE simulations.



Figure 1. Changes in compositional and structural attributes of a boreal mixedwood stand over a 250-year simulation period in SORTIE.

Conclusion

The stand dynamics model SORTIE effectively simulated changes in stand structural attributes that collectively defined four periods of stand development. SORTIE appears to be a promising tool for projecting the structural dynamics of complex stands, and the capacity of such stands to support different biological communities over time.

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FVS^{Ontario}: Software to Model Silvicultural Responses in Complex Stand Structures

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Introduction

Over the last five years, Ontario has undertaken the calibration of the Forest Vegetation Simulator Model (FVS) for Ontario. All of the currently available growth and yield models are at the stand level. These continue to be adequate for simple even-aged clearcut scenarios. However, besides clearcutting, Ontario employs single-tree selection and shelterwood silvicultural systems. As well, forecasted wood supply shortages have led to a focus on intensive forest management including density regulation. The current stand level models are limited in their ability to predict the effects of mid-rotation density regulation or any tree-level silvicultural decisions. FVS, the official growth model of the USDA Forest Service, was a strong candidate to complement the existing stand level models.

The first step in adapting FVS was to take the metric user interface from PrognosisBC and the coefficients from LS-Twigs and test for logical behavior (Lacerte et al. (2004). The next step was to develop new model forms based on the available Ontario growth and yield permanent sample plot (PSP) data (Lacerte et al. 2006a, 2006b). Approximately 500 PSPs are remeasured annually in Ontario. This paper reports on the latest enhancement of the models (species and range of conditions) currently available in FVS^{Ontario} (version 3.0). This includes calibration and validation of the following models:

- crown ratio model;
- small and large tree (diameter at breast height) Dbh increment equations;
- height-Dbh curve for height dubbing of small and large trees and expand the number of species; and,
- improved tolerant hardwood diameter increment equation that includes a stem quality or vigour attribute to the model form

The user interface was modified to be compatible with Ontario's forest management methods including the addition of single-tree selection and shelterwood screens that incorporate prescriptions for these silvicultural systems.

Data

Individual tree growth data used in modelling efforts were obtained from the provincial growth and yield

database maintained by the Ontario Ministry of Natural Resources. Approximately 10% of the data were reserved for validation. Different datasets were used for fitting each model (for example, Dbh growth was available from most trees while height measurements were only available from a sample) and separate validation data were reserved for each model.

Model Components

Crown Ratio Equation

A new crown ratio (CR) prediction model was developed using the expanded provincial data set. A form of the monomolecular growth equation (Vanclay 1994 p. 110) was selected. Since the correlations between crown ratio and the independent variables were weak, a simple model form was selected that predicts CR as a function of Dbh and basal area (BA).

The inclusion of CR into the other subsequent model forms did not add any advantage to the predictions and was not used. This was due to the fact that Dbh and BA (components of the CR equation) are implicitly accounted for in the majority of the other model forms

Dbh Growth Equations

The model of Wykoff (1990) was modified slightly so Dbh growth is a function of Dbh, the basal area of live trees larger in Dbh than the target tree (BAL), height of the target tree, the SI of the stand, the stand BA, the stand quadratic mean Dbh (Dbhq) and quality attribute (AGS¹).

Dbh growth increases with Dbh to a maximum and then growth declines (Figure 1). Typically the coefficients associated with height, BAL and BA predicted an increase in Dbh growth with a decrease in the independent variable. The coefficients associated with SI, Dbhq, and AGS predicted an increase in Dbh growth with an increase in the independent variable. The AGS term is non-zero only for tolerant hardwoods and indicates the tree had good quality (high value) and likely to maintain that quality in the future.

Height Dubbing

The height-Dbh equations were revised to reflect the expanded dataset. The new equation is a modified

¹ AGS (acceptable growing stock) – a quality assessment of stem vigour and likelihood to maintain its current status

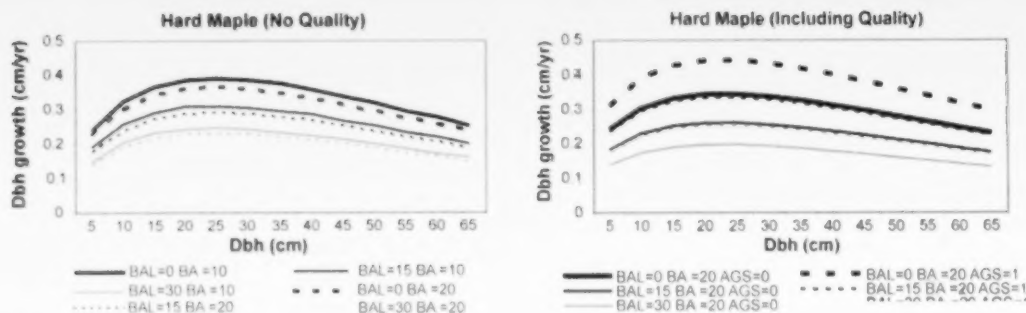


Figure 1. Dbh growth equation for Hard Maple

Weibull function where the asymptote has been expanded to incorporate site variables and includes Dbh, SI and BA terms. Peng (1999) found the Weibull model form had satisfactory results for predicting height from Dbh in Ontario.

Small-Tree Height Growth Model

The new small tree height growth model is similar to the previous conifer small tree height growth model used in Lacerte (2006a). Height growth increases as a function of height up to a maximum and then declines. Increasing SI has a positive effect on height growth BAL has a negative effect. The SI and BAL terms were only included if they were statistically significant ($\alpha = 0.05$).

Small Tree Dbh Growth Equation

Limited small tree data is available in the Ontario data set and as a result the large tree height-Dbh model was inverted to predict small tree Dbh. This equation loses the statistical properties (least squares) of the original formulation but maintains compatibility between Dbh and height.

User Interface Screens

FVSOntario offers a suite of management user interface screens to simplify model use. These screens include provisions for: establishment of natural stands or plantation scenarios, thinning from above or below to a density, basal area or crown closure target, thin by diameter class and by species, implementing shelterwood treatments and implementing single tree selection treatments. In addition, a keyword set can be submitted to the model to undertake additional treatments of increasing complexity.

Discussion and Conclusions

Improving FVS's prediction capabilities and acceptance as an additional decision support tool for forest management planning in Ontario continues to be a priority. The accomplishments made to date have been through a collaborative effort with forest industry (Tembec Forest Research Partnership) and provincial (Ministry of Natural Resources) and federal government (CFS – Laurentian Forestry Centre) partnerships.

Additional collaborative efforts has been recently undertaken with Michigan Technological University to involve their graduate students in expanding the model's potential. The rapid development of FVSOntario has been the result of open collaboration with the USDA Forest Service, British Columbia Ministry of Forests and ESSA Technologies. We are very appreciative of their willingness to provide their products and their guidance to our efforts.

FVSOntario version 3.0 is a more stable software platform within which silvicultural gaming can be undertaken. The expanded growth and yield data set used for model enhancement has greatly improved the prediction properties for the range of conditions tested through the validation procedure. Work is continuing on linking FVS to inventory attributes including the development of a tree list generator. A concurrent project is looking at LIDAR and high-resolution digital imagery for providing more detailed inventory information at the tree level for each stand. This technology has the potential to supply the FVS the input requirements necessary to be implemented at a large scale.

Opportunities to use the model, receive training and provide feedback will occur during the fall of 2007 during a series of planned workshops. More information about FVSOntario can be found at www.FVSOntario.ca.

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Integration of Ethno-Botanical Uses and Conservation Practices of Lesser-Known Species in the Analysis of Diverse Humid Tropical Forest Stand and Structure: The Case of Region 8, Philippines

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Introduction

Conservation of genetic resources must be done for sustainable management and development of forest resources, especially the endemic tree crops which are rich in genetic diversity. Forests in Eastern Visayas, like other tropical forest ecosystems, are highly diverse. They are replete with timber species that have multiple uses and a significant number came from the lesser-known species (LKS) populations (Table 1). LKS, as they are called, are not popular compared with dipterocarps and other commonly used commercial species. But they have already been put into use in many forms by local people and other forest users. Their ethnobotany is substantially interesting. Ethnobotany refers to the study of the interactions between people and plants (Martin 1996). Though it is not yet extensively explored as far as Region 8, Philippines is concerned, the interest to study local people's relationship with trees is increasingly growing. This development stems from the recognition of local people's role in forest conservation efforts and thus should be factored in the development of models to analyze complex stand and structure of a humid tropical forest.

Materials and Methods

The gathering of information was done through informal and structured interviews and researcher's observations, primary data collection supplemented with bibliographical researches. To relate ethnobotany to stand structure dynamics, a representative species was selected to demonstrate the ecological role and economic usefulness of LKS. In this study, bagalunga (*Melia dubia* Cav.) was the focus of investigation.

Results

Ethnobotanical Uses

Represented by bagalunga (*Melia dubia* Cav.), results of the survey revealed that respondents had widely used LKS. The wood had been used for house construction particularly as wall boards, flooring materials and as door panels and jalousies, though LKS ranked lower than the commonly used commercial hardwood species, like the dipterocarps and *Pterocarpus* spp. It is also used as firewood, boxes or crates, coffin, furniture and as the keel of boats. Few mentioned that the wood is a good material for the manufacture of wooden slippers; *bagalunga* was used as inert material in making firecrackers. A number of local people claimed that

Table 1. Stand and stock information of some LKS in Eastern Visayas, Philippines

SPECIES		FAMILIES	TOTAL VOLUME (m ³ /ha)	
Common Name	Scientific Name		Old Growth	Residual
1. Ulayan	<i>Lithocarpus bennettii</i>	Fagaceae	4.8	5.8
2. Duguan	<i>Myristica philippinensis</i>	Myristicaceae	3.7	3.0
3. Nato	<i>Palaequium luzoniense</i>	Sapotaceae	3.2	
4. Bitanghol	<i>Callophyllum blancoi</i>	Guttiferae	3.2	1.9
5. Bolong -eta	<i>Diospyros pilosenthera</i>	Ebenaceae		1.5
6. Antipolo	<i>Artocarpus blancoi</i>	Moraceae		1.1
7. Balobo	<i>Diplodiscus paniculatus</i>	Tiliaceae		1.1

Source: Mosteiro (undated)

LKS is potentially used for soil fertility recovery due to its high biomass. This confirms earlier study of Balbarino *et al.* (1992) on farmer's evaluation of tree and shrub species in calcareous agri-ecosystems of Matalom, Leyte, Philippines which revealed that *bagalunga* is the farmer's choice as one of the best five species for mulching/soil fertility recovery.

Conservation Practices

Genetic conservation was part of the farming system in some areas where *bagalunga* was found abundantly growing. The farmers were not only users but conservers of this plant genetic resource. Many claimed to have grown it using either wildlings (young regenerations) and seeds, protected those that were naturally growing. They know the best time for planting. Planted wildlings/seedlings were cared for in the same manner as for other agricultural crops grown in the farm like abaca, coconut, etc. Other people, however, just leave nature to perform its course. Some local people are knowledgeable of the flowering and fruiting characteristics, time of seed collection and shedding-off of leaves of *bagalunga*.

Discussion

Bagalunga, like any other LKS as claimed by many respondents, has strong potential for domestication in the uplands. Arroyo (1990) declared that *bagalunga* for one, has good qualities and characteristics, to wit: 1) relatively fast-growing; 2) good tree form; 3) coppicing ability; 4) known economic uses for its wood which is much appreciated in areas where they occur; and 5) observed to be a prolific seeder. Lim and Farida-Hanum (1992) also reported that, in general, indigenous species are already adapted to local conditions and their genetic base is already accessible. *Bagalunga*, being indigenous, is distributed in a wide range of soil types and habitats from seacoast to hills and mountainsides (Nasayao, *et al.*, 1994).

Existence and relative abundance of LKS population serve as a seemingly strong indicator of forest stand and structure dynamics. There are two things that would explain this: human ecological zones and ecological succession which are very much closely interrelated with each other. Based on observations gathered from the study, LKS proliferate in zones where human settlements exist. In fact, most of the respondents were parties to the community-based forest management (CBFM) tenurial arrangement with the government. This corroborated with the observations of Martin (1995) that human settlements are usually found at a mid-montane zone, giving

inhabitants easy access to lands and produce from throughout the territory. The timber stand in this instance is structurally different from that of the primary or climax forest. As ecological succession takes place, the dominant timber species are the pioneering LKS which offer multiple uses to people and to the bio-physical site. Vergara (1999) said that inhabitants surrounded as they are by all the existing genetic, ecosystems and cultural variations, cannot help but become aware of and knowledgeable about such diversity and the benefits derived therefrom. Shulte (2002) added that people are often successful in perpetuating the productive capacity of the forests.

Conclusion

LKS grow in relative abundance in Region 8, Philippines and their economic value cannot be over-emphasized even if they play the role of substitutes to the commonly used commercial hardwood species. They showed the potential for domestication, noteworthy of which are those belonging to families *Meliaceae*, *Moraceae* and *Sapotaceae*. Farmers and other people who are directly and indirectly dependent on forest resources are sources of knowledge on the uses and conservation practices of LKS. The biological and economic functions associated with LKS establish a foundation which influences relationships between people and trees and these should be factored in the development of models to analyze complex stand and structure of a tropical humid forest.

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Effects of Age, Productivity, and Disturbance History on Forest Structure in a Managed Boreal Forest Landscape

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Introduction

As alternative forest management strategies emerge that use silvicultural interventions to emulate the structural complexity of older forests, it becomes essential to better understand relationships among structural diversity, forest age, and disturbance history to proceed with confidence. Inspired by the multi-cohort forest management (MFM) concept (Bergeron et al. 2002, Harvey et al. 2002), we recently developed a structural classification approach for boreal mixedwood and spruce forest types in northeastern Ontario. Similar to previous multi-cohort classification studies in Quebec, we relied on increases in tree size diversity and features of diameter distributions to classify stages of multi-cohort structural development (Nguyen 2000, Boucher et al. 2003). Our classification is based on a suite of tree diameter- and canopy strata-related variables and separates even-aged stands, in which stem diameters tend to be normally distributed (class 1), from uneven-sized stands that display more irregular (class 2) or inverse-J (class 3) type diameter distributions across a wider range of diameter classes (Kuttner 2006; Kuttner & Malcolm *in prep.*). This structure-based classification now enables us to examine correlates of structural complexity in managed boreal forests. The objective of the present study is to evaluate the relative influences of stand age, disturbance history, and site productivity on structure class membership in a managed boreal forest landscape.

Methods

Our structural classification study relied on data from Ontario's network of permanent growth and yield monitoring plots, and included lowland spruce ($n=108$) and mixedwood ($n=308$) sites located throughout Ecoregion 3E in northeastern Ontario. Following Boucher et al. (2006), productivity indices were developed using residuals from regressions of stand height against stand age. Stand ages were calculated using the mean age of tree increment cores from dominant and co-dominant trees. Disturbance history (horse-logged, mechanically logged, or unlogged) was determined for a subset of the spruce ($n=47$) and mixedwood ($n=115$) sites through site visits and reviews of historical documents.

We used generalized logistic regression models to assess the significance and relative influences of stand age, productivity index, and disturbance history in determining structure class membership in both forest types. The probabilities of response categories were modeled as two separate logits (comparing structure classes 2 and 3, respectively, to structure class 1). Standardized effect coefficients were used to compare the relative strengths of the independent variables. In addition, we evaluated classification success by comparing predicted class memberships against actual classification results.

Results

Both stand age and the logarithm of stand age were significant predictors of stand height in mixedwoods ($R^2 = 0.43$), but only the logarithm of stand age was significant for spruce sites ($R^2 = 0.26$). Rank-transformed and normalized residual scores from these regressions provided productivity indices. Logistic regression models that included stand age, productivity index values, and disturbance history variables showed that disturbance history was not a significant predictor of class membership among either mixedwood or spruce stands ($p=0.49$, $p=0.18$, respectively). Stand age and relative productivity index variables, however, were significant predictors in all class-specific comparisons for both forest types. We therefore developed reduced models without disturbance history to quantify and interpret age and productivity effects and to examine classification success.

Increases in both stand age and productivity index were positively associated with probabilities of membership in increasing complex structure classes in both forest types. In mixedwoods, stand age was approximately twice as influential as productivity in predicting class membership. By contrast, in spruce sites, stand age and productivity were approximately equally influential in determining class membership and productivity was a slightly better predictor of complex class 3 structure than age. Classification success averaged 66% overall for both the mixedwoods and spruce groups. In mixedwoods, classification success declined from class 3 (82%), to class 1 (66%), to class 2 sites (46%). Conversely,

classification success for spruce sites was highest for class 1 (83%), and declined for increasingly complex class 2 (61%) and class 3 (59%) sites.

Discussion

Although we expected disturbance history to be a significant predictor of structure class membership, our results in both forest type indicated it was not given that age and productivity were included in our models. Stand development over time, combined with variability in the amount and type of residual leave following logging events, may have obscured logging effects. Model results agreed with our expectations in the mixedwood forest type, in that age was shown to be substantially more influential than productivity in predicting class membership, and in that these variables together predicted membership in the most complex structure class well. Results for spruce sites, on the other hand, suggested that the likelihood of exhibiting irregular class 2 or inverse-J class 3 diameter distributions was as much a function of differences in site productivity as stand age, and classification success decreased in increasingly complex structure classes. Overall, the positive relationships between site productivity and structural diversity evidenced in our study accord with Boucher et al.'s (2006) recent findings in Quebec that productive stands become uneven-sized earlier and maintain greater diameter diversity than unproductive ones. Harper et al. (2005) also found that productivity differences influenced the timing of structural development in spruce forests, and could not identify distinct stages of structural development in organic sites between 40-300 years old. It may be that some of the oldest spruce sites in our study show irregular rather than inverse-j diameter distributions due to low site productivity, deep peat layers, and lack of mineral seedbeds that together might limit tree densities, canopy closure, self-thinning, and recruitment in gaps (Franklin et al. 2002, Foster 1985, Harper et al. 2002).

Over 30% of sites in both forest types were misclassified using our models. Clearly, additional factors influence tree size diversity, which leads us to question the degree to which our structural classification reflects successive stages of stand development, especially in lowland spruce forest (Bergeron et al. 1999, Harper et al. 2005). We found that all three structure classes were represented in

most forest age classes in both forest types. Perhaps because our structural classification did not consider dead wood abundance, and included harvested sites with varying degrees of tree retention, it failed to correspond as well as we had anticipated with forest age (Harper et al. 2005). Collectively, our findings indicate that manipulating stand size structure alone may not necessarily emulate progressive stages of stand development. We agree with other MFM proponents that silvicultural interventions to emulate the complex multi-cohort age structure of relatively old boreal stands also incorporate targets for the maintenance of other age-related stand structural features, such as standing deadwood and downed woody debris, to maximize MFM's potential to meet multi-cohort age structure emulation objectives (Harvey et al. 2002).

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